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ABSTRACT

This technical specialty course is one of thirty-five courses designed for use by two-year postsecondary institutions in five nuclear technician curriculum areas: (1) radiation protection technician, (2) nuclear instrumentation and control technician, (3) nuclear materials processing technician, (4) nuclear quality-assurance/quality-control technician, and (5) nuclear reactor (plant) operator trainee. This course, Control Systems I, contains six modules: Introduction to Block Diagrams, Input/Output Devices, Control System Theory, Pneumatic Control Mechanisms, Control Valves, and Process Characteristics. Each module follows a typical format including the following sections: introduction, module prerequisites, objectives, subject matter, exercises, materials, procedures, data tables, reference materials, and tests. (A master index and suggested program planning guides are also available--see CE 026 856 and CE 026 639-643.) (LRA)

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ED192151

Nuclear Technology Series

# COURSE 33

# CONTROL SYSTEMS I

CENTER FOR OCCUPATIONAL RESEARCH
AND DEVELOPMENT

4800 LAKEWOOD DRIVE
WACO, TEXAS
76710

CE 026 283

U.S. DEPARTMENT OF HEALTH, EDUCATION & WELFARE
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# PREFACE

## ABOUT NUCLEAR TECHNOLOGY MODULES

The modules – developed for use in two-year postsecondary technical institutions to prepare technicians for employment – are useful in industry for updating employees in company-sponsored training, and as laboratory texts in engineering schools. The principles, techniques and skills taught in the modules, based on tasks that nuclear technicians perform, were obtained from a nationwide advisory committee of employers of nuclear technicians. Each module was written by a working technical expert/experienced writer team and tested with students.

A module contains the following elements:

Introduction, which identifies the topic and often includes a rationale for studying the material.
Module Prerequisites, which identify the material a student should be familiar with before studying the module.
Objectives, which clearly identify what the student is expected to know for satisfactory module completion. The objectives, stated in terms of action-oriented behaviors, include such action words as operate, measure, calculate, identify and define, rather than words with many interpretations, such as know, understand, learn and appreciate.
Subject Matter, which presents the background theory and techniques supportive to the objectives of the module. Subject matter is written with the technical student in mind.
Exercises, which provide practical problems to which the student can apply this new knowledge.
Materials, which identify the equipment required to complete the laboratory procedure.
Procedures, which is the experiment section, or "hands-on" portion of the module (including step-by-step instruction) designed to reinforce student learning.
Data Tables, which are included in most modules for the first year (or basic) courses to help the student learn how to collect and organize data.
Reference Materials, which are included as suggestions for supplementary reading/viewing for the student.
Test, which measures the student's achievement of the prestated objectives.

A helpful Index has been added at the end of each course.

The materials contained herein were developed pursuant to a contract with the Office of Education, U.S. Department of Health, Education and Welfare: Contract No. 300780582. Contractors undertaking such projects under Government sponsorship are encouraged to express freely their professional judgment in the conduct of the project. Points of view or opinions stated do not, therefore, necessarily represent official Office of Education position or policy.

The Nuclear Technology Series consists of five curricula:

Nuclear Reactor (Plant) Operator Trainee.
Radiation Protection Technician.
Nuclear Materials Processing Technician.
Nuclear Quality-Assurance/Quality-Control Technician.
Nuclear Instrumentation and Control Technician.

The completed Nuclear Technology Series consists of the following 35 technical specialty courses:

Radiation Physics.
Radiation Protection I.
Principles of Process Instrumentation.
Heat Transfer and Fluid Flow.
Introduction to Nuclear Systems.
Instrumentation and Control of Reactors and Plant Systems.
Reactor Operations.
Reactor Safety.
Reactor Auxiliary Systems.
Power Plant Systems.
Radiation Detection and Measurement.
Reactor Physics.
Power Plant Chemistry.
Introduction to Quality Assurance/ Quality Control.
Metallurgy and Metals Properties.
Mechanical Component Characteristics and Specifications.
Radiation Protection II.
Radiological Emergencies.
Radiation Shielding.
Radiation Monitoring Techniques (Radiochemical).
Radioactive Materials Disposal and Management.
Advanced Radionuclide Analysis.
Nuclear Chemical Processes.
Nuclear Systems and Safety.
Radioactive Material Handling Techniques.
Nondestructive Examination (NDE) Techniques I.
Metrology.
Welding Inspection.
Civil/Structural Inspection.
Mechanical Inspection.
Quality-Assurance Practices.
Nondestructive Examination (NDE) Techniques II.
Control Systems I.
Control Systems II.
Power Plant Electrical Systems and Components.

Availability: Instructional modules are available individually or by courses from:

Center for Occupational Research and Development
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Printed:

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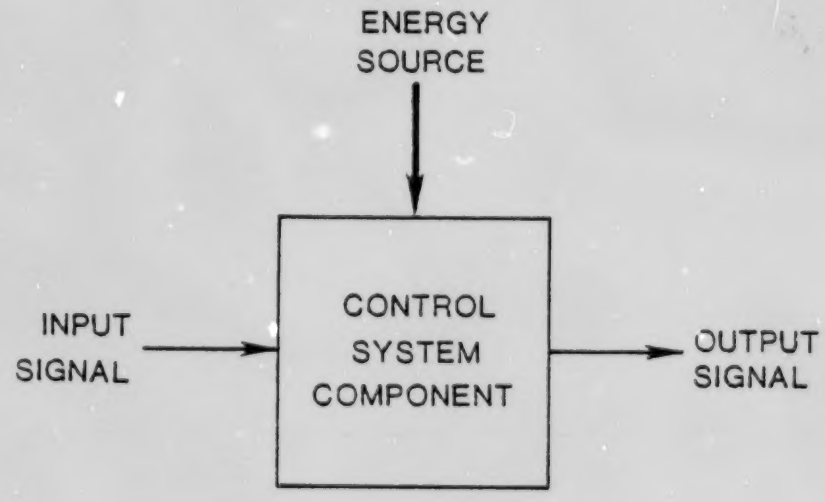
# NUCLEAR TECHNOLOGY

## MODULE 33 - 1

INTRODUCTION TO BLOCK DIAGRAMS




CONTROL SYSTEMS I

COURSE 33

ORD CENTER FOR OCCUPATIONAL RESEARCH AND DEVELOPMENT

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COURSE 33 CONTROL SYSTEMS I

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# INTRODUCTION

Complex equipment or processes are best understood and analyzed by mentally "breaking a system apart" into its major functional components, or subsystems. Each subsystem then can be studied individually; sometimes a subsystem is still too complicated to understand in its entirety, and it must also be subdivided into component parts for closer examination. Once the component parts are understood, they can be mentally "put back together" to understand the operation of the complete system. During this reconstruction process, one must understand how the component parts, or subsystems, relate to one another. Frequently, the "output" of one subsystem becomes the "input" of a related subsystem; the behavior of the first subsystem, therefore, affects the behavior of the second.

When we mentally "break a system apart," we often find that our thoughts are best organized and remembered if we have some symbolic, visual, or graphical representation of the system. One such visual model is called a "block diagram." Blocks in the diagram can represent a subsystem or component, and lines connecting the blocks indicate that two or more subsystems are related (or connected together) in some manner. Unnecessary details are omitted from block diagrams.

Many control systems employed in the control of nuclear applications are complex and require use of block diagrams for simplification and understanding. The purpose of this module is to define terms and to introduce techniques for use of block diagrams in representing complicated processes and hardware arrangements.

## MODULE PREREQUISITES

The student should have completed Course 3, "Principles of Process Instrumentation"; Course 5, "Introduction to Nuclear Systems"; and Course 6, "Instrumentation and Control of Reactor and Plant Systems."

## OBJECTIVES

Upon completion of this module, the student should be able to:

1. Use labeled block diagrams to represent a given system with as many as five identifiable components.
2. Define the following terms:
   - System.
   - Control-closed-loop and open-loop.
   - Control system.
   - Feedback.
   - Feedforward.
3. Draw and label a block diagram that visually represents –
   - An open-loop system.
   - A closed-loop system.
4. Describe the meaning of –
   - An input-output relationship.
   - A transfer function.
5. Draw and label the canonical form of a feedback control system.
6. Describe the size and timing relationship of two components of a control system.

## DEFINITIONS

Before undertaking the study of block diagrams, the student must become familiar with, and know the meanings of, the following terms:

- Feedforward is a system by which process control is accomplished by maintenance of a balance between supply and demand on a process by measurement of both demand potential and demand load. From this information, a supply is manipulated in accordance with a mathematical expression that relates all inputs and outputs on the process.
- A system is an integrated assembly of functional hardware devices designed, selected, and interconnected in such a manner as to perform a specific function of a higher level than could be performed by any of the individual devices.
- Control is the procedure by which a condition or set of conditions is caused to be enacted upon a medium.
- A control system is an arrangement of hardware and/or software components that has the ability to maintain an exact, preselected set of conditions on a process.
- Feedback is a situation by which a portion of a system output is routed back to the input to provide system stabilization. In control systems, the term is used to specify a scheme that utilizes a signal that represents the condition of the controlled variable. This signal is connected to the input of the controlling means and helps to determine the controller output.

## BLOCK DIAGRAMS

The beginner in the field of instrumentation may have difficulty understanding even the most basic systems. Fortunately, however, most instrumentation manuals and texts present an orderly approach, which usually begins with systems analysis. The term "systems analysis" refers to an engineering technique that breaks down complex technical problems into basic elements and subsystems whose interrelations are presented in simplified form for clearer understanding.

The systems approach is used as a basic concept to place emphasis upon component parts of the system and the functions performed by these parts. A part of the system that performs specific tasks first is represented as a simple "black box" in the block diagram. The black box then can be explained in more detail as a subsystem with detailed construction, circuits, manufacturing specifications, and other relevant information.

Most people are familiar with an automobile and the function it performs. An individual with little mechanical background or inclination may have difficulty understanding or explaining the operation of the entire automobile system. The block diagrams in Figures 33-1-1, 33-1-2, and 33-1-3 would simplify the operation and, therefore, assist the individual in learning about the automobile. The different sets of diagrams illustrate different operational concepts.

The block diagram in Figure 33-1-1 lists the major subsystems of an automobile. Lines connecting the blocks signify the interrelationships between the components. They indicate that the component parts are connected in some way. The power plant subsystem can be explained further by use of another block diagram (Figure 33-1-2).

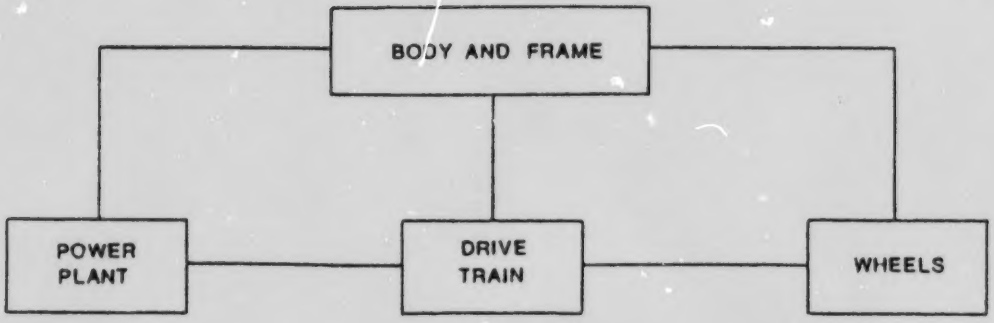



Figure 33-1-1. Block diagram of automobile.

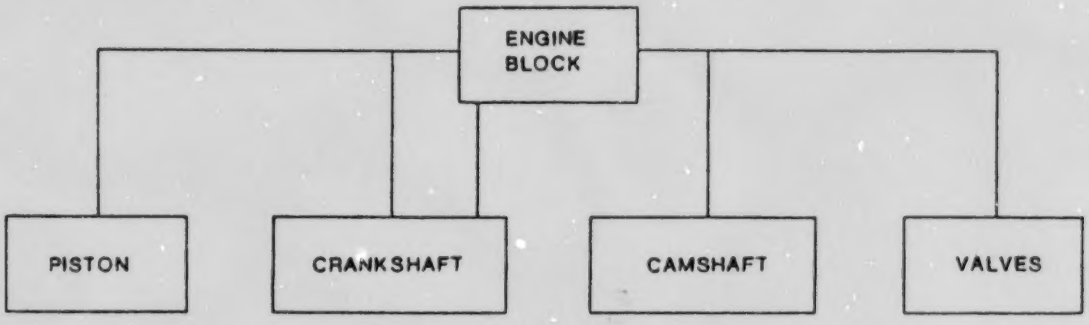



Figure 33-1-2. Block diagram of an automobile power plant.

In Figure 33-1-2, the power plant, a subsystem of the automobile, has been shown to contain more basic component parts. An explanation of these parts, althought not undertaken in this module, and their relationships to the major system would help one to understand the system.

Another block diagram (Figure 33-1-3) could be used to illustrate the automobile's ignition system. Explanation of the individual components and their operation would allow

increased understanding of the entire system.

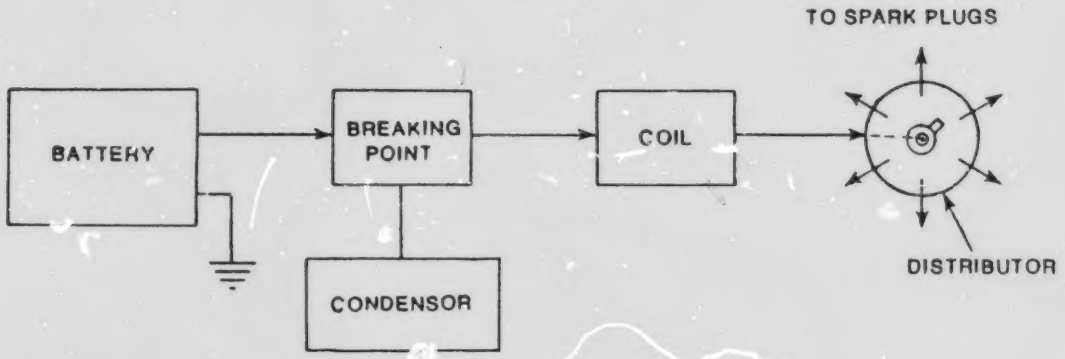



Figure 33-1-3. Automobile ignition system.

The previous block diagrams were used to relate operation of a major system to the combined operation of the individual component parts. Other block representations could relate the output signal to the input signal with respect to the function performed in accordance to size and timing relationships. (See Figure 33-1-4.)

The control-system components in Figure 33-1-4 produce an output that has an exact relationship to the input. The amplifier produces an output equal to the product of the input and the amplifier gain. A signal to the valve determines the valve position, which governs an amount of flow through a pipe. The flow transmitter generates an output signal that is a function of fluid flow. An electric motor's speed is determined by voltage applied to the armature, and output of a process controller is a function of the input. The relationship between input and output of the device is a function of the component gain; for example,

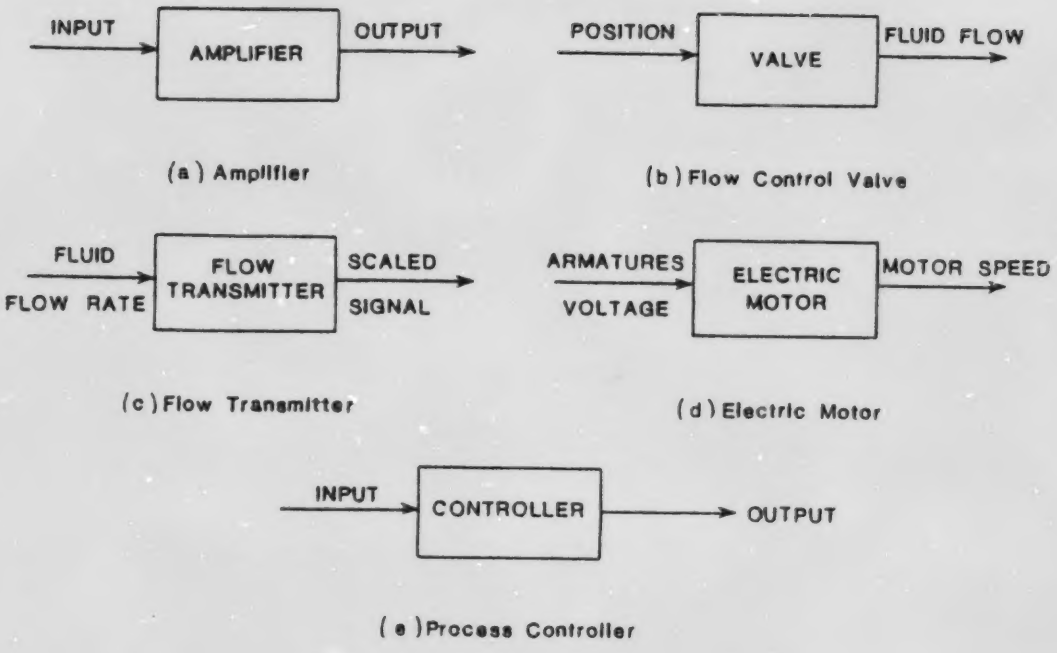


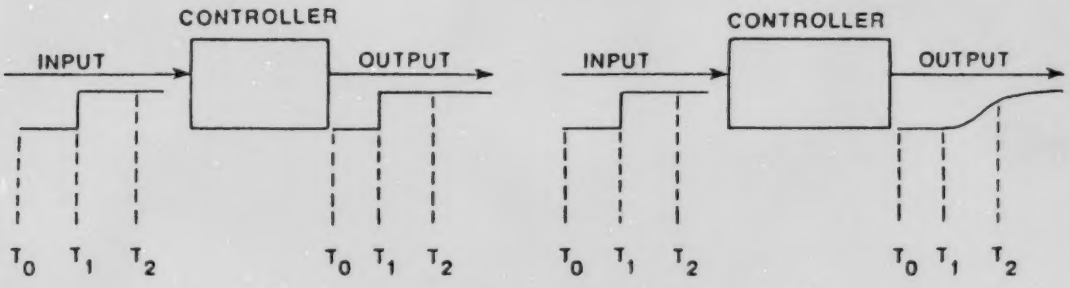

Figure 33-1-4. Block representation of control system components.

a high-gain amplifier will produce a very large output signal for a given input, and a low-gain amplifier will produce a much smaller output for the same signal.

Another characteristic that can be represented by a block diagram is that of the time relationship between the input and the output of a system. With the exception of the process controller, the "dead time" of the system is the only time relationship between input and output. Dead time is time lost as the information travels through the system. In electrical systems, dead time usually is negligible. When input to an amplifier is changed, the output change is instantaneous. Dead time in other components normally is small compared to other time losses in a complete

system. (More will be said about dead time in other modules of this series.)

The timing relationship between input and output of the controller is an important consideration that can be represented by block diagrams. If the controller output changes as soon as the input change occurs, there is no phase shift in the signal in and signal out; and the controller acts as an amplifier (Figure 33-1-5a). If, on the other hand, the controller produces a time relationship between input and output, a phase shift exists between the two signals (Figure 33-1-5b). The transfer function of a component establishes the size and timing relationship between input and output.




(a) Controller Without Phase Shift (b) Controller With Phase Shift

Figure 33-1-5. Controllers with and without phase shift.

At $T_0$, the input and output of both controllers are at a stable value. At $T_1$, the input suddenly is increased. Output increases at the same time in the controller in Figure 33-1-5a. In Figure 33-1-5b, the output does not reach

a new level until $T_2$. The time between $T_1$ and $T_2$ in Figure 33-1-5b is a result of the phase shift between the input and output signals.

A component's gain also can be represented by a block diagram in which the input and output signals are properly scaled. In Figure 33-1-5a and b, the gain is unity because of equal amplitude of the signals. In Figure 33-1-6a, however, the gain has increased by two because amplitude change in the output signal is twice that of the input. Figure 33-1-6b represents a gain of 0.5 because amplitude change in the output signal is one-half that of the input.

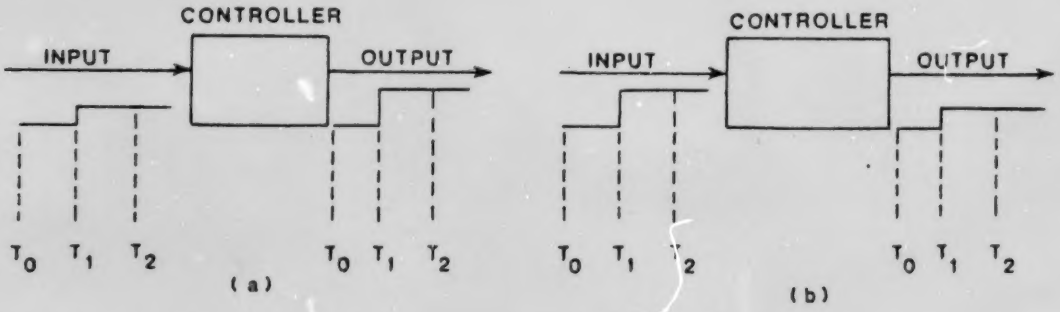



Figure 33-1-6. Block diagram representation of controller gain.

Component parts can be connected in such a manner as to represent complex systems. An understanding of each component can lead to a better comprehension of the total system. The components, for example, of an open-loop control system are represented in Figure 33-1-7.

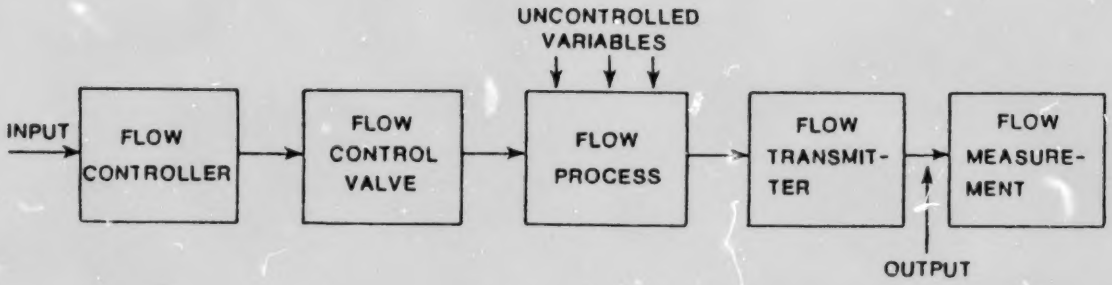



Figure 33-1-7. Components in an open-loop control system.

Operation of each component except the flow process has been explained. Flow of fluid through a pipe is a flow process, and control of this flow constitutes a flow-control system. To understand the open-loop system in Figure 33-1-7, assume that the fluid flow initially is at a steady value and that the flow transmitter is measuring this flow. With a change in input to the controller, output will change. Controller output either can increase or decrease with an increase in input. For controllers used in open-loop control applications, however, output normally increases with an increase in input. This is called a "direct-acting controller." Control valves also can open or close upon an increase in signal from the controller. In this example, it will be assumed that the valve opens upon a signal increase. This valve is an air-to-open type.

When a process operator desires an increase in flow, input to the flow controller will be increased, causing the valve to open and to increase flow through the process line. The flow transmitter responds to this increase in flow. The operator adjusts the regulator on the controller input until flow measurement on the system output is at the desired value.

The control system just described is designated as an open-loop one because there is no connection that allows information to be recycled in the system. Thus, there is no automatic compensation for process changes: Fluid flow through the control valve is a function of pressure drop across the valve. If the valve is in a fixed position and if the static pressure upstream of the valve decreases because of increased flow or a reduction in pump pressure, the pressure drop across the valve will decrease, resulting in a decrease of flow. The open-loop control system has no way of compensating for this, and flow will remain at a value lower than desired. The open-loop system represented by the block diagram in Figure 33-1-7 is shown schematically in Figure 33-1-8. For a fixed-valve position, an increase in uncontrolled flow at A or B could result in a decrease in controlled flow.

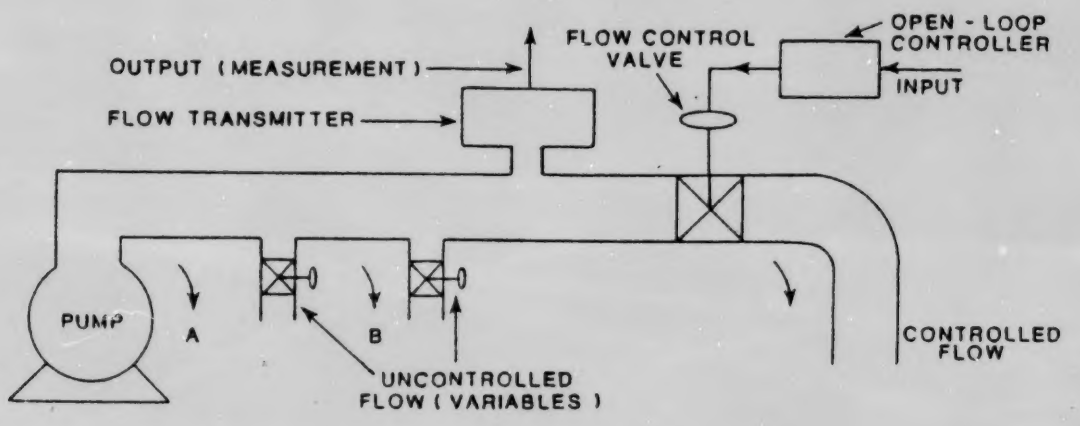



Figure 33-1-8. Schematic of an open-loop control system.

Because of the inability of the open-loop control system to correct for uncontrolled process disturbances, use of these systems in limited. A better method of process control is depicted in Figure 33-1-9. Information can be recycled within the system by means of the "feedback link."

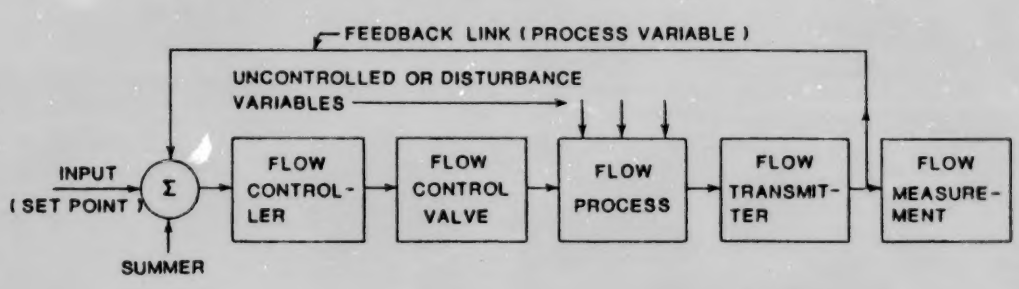



Figure 33-1-9. Block diagram of a closed-loop control system.

The feedback link is the means by which the process condition (measurement) is conveyed to the controller. The system "input" (set point) is applied to an algebraic summer and tells the controller the desired condition at which the process is to be maintained. When actual process conditions are different from the desired conditions, an error exists in the system. The difference in the two signals is called the "error signal." The purpose of the control loop is to drive the error signal to zero and keep it there. When this is accomplished, the set point is equal to the process variable (S.P. = P.V.), and the system is controlled. A change in process caused by a disturbance variable causes a difference between the process variable and the set point. This difference is known as "offset," which usually is applied to a steady-state difference between measurement and set point.

The offset is applied to the controller input, which generates an output that changes the process until the offset is zero. (A more detailed coverage of this concept will follow in Module 33-3, "Control System Theory.") A schematic representation is given in Figure 33-1-10. Notice the similarities and differences between Figures 33-1-7 and 33-1-8 and Figures 33-1-9 and 33-1-10.

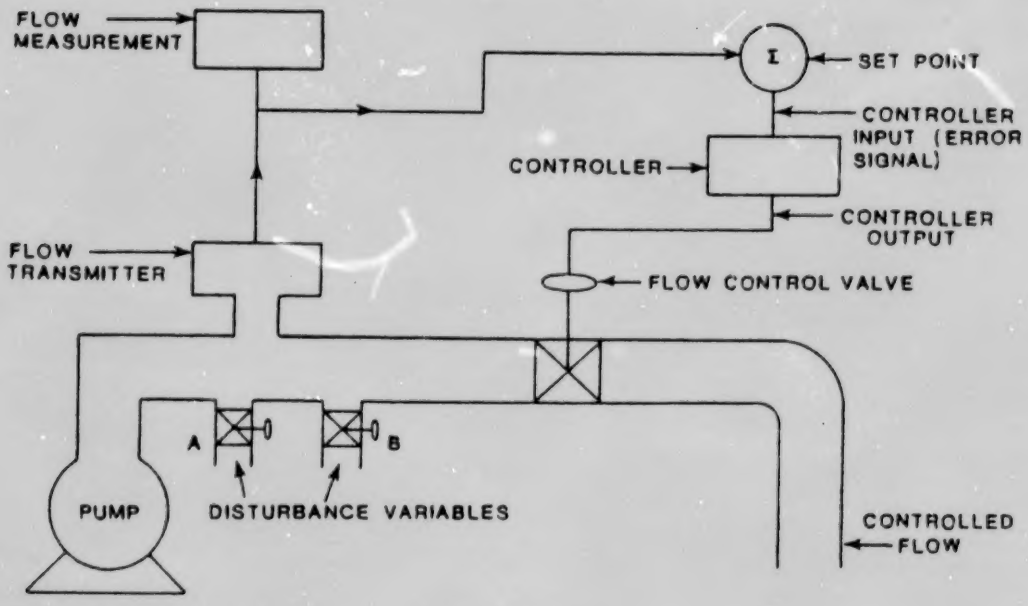



Figure 33-1-10. Schematic of a closed-loop control system.

The previous discussion explained use of the control system representation by means of block diagrams. System components were represented by blocks in black boxes. This terminology signifies the importance of the component function and not its actual operation. The components used in the closed-loop shown in Figure 33-1-9 and 33-1-10 can

be of any type. The flow transmitter, for example, can be electronic or pneumatic and can operate on any of the many flow measuring principles, which include differential pressure, magnetic, turbine, ultrasonic, or vortex shedding.

Each component used had both input and output and acted on the input in some prescribed fashion to generate the output. The difference between component input and output is established by the transfer function, which determines the amplitude and timing relationship between the two signals.

Most control systems are either open- or closed-loop, and many operate on the principle of feedback. Some complex processes, however, utilize a control concept called "feedforward." Before feedforward control can be applied effectively to a process, the process must be completely understood. A mathematical equation that states the material and energy balance must be written. Feedforward control is an advanced control principle that will be covered in detail in a later module in this series. A feedforward control application and block diagram of the control scheme will be given now, however, to illustrate the importance of block-diagram representation. A feedforward level control process is presented in Figure 33-1-11.

The level in the process of Figure 33-1-11 will be constant if flow out is made equal to flow in by the feedforward controller, which computes a signal to position the valve on the line leaving the tank. This signal is derived from an equation that relates level to the flow in and flow out of the process. Note: In the feedforward control system, level measurement is not required.

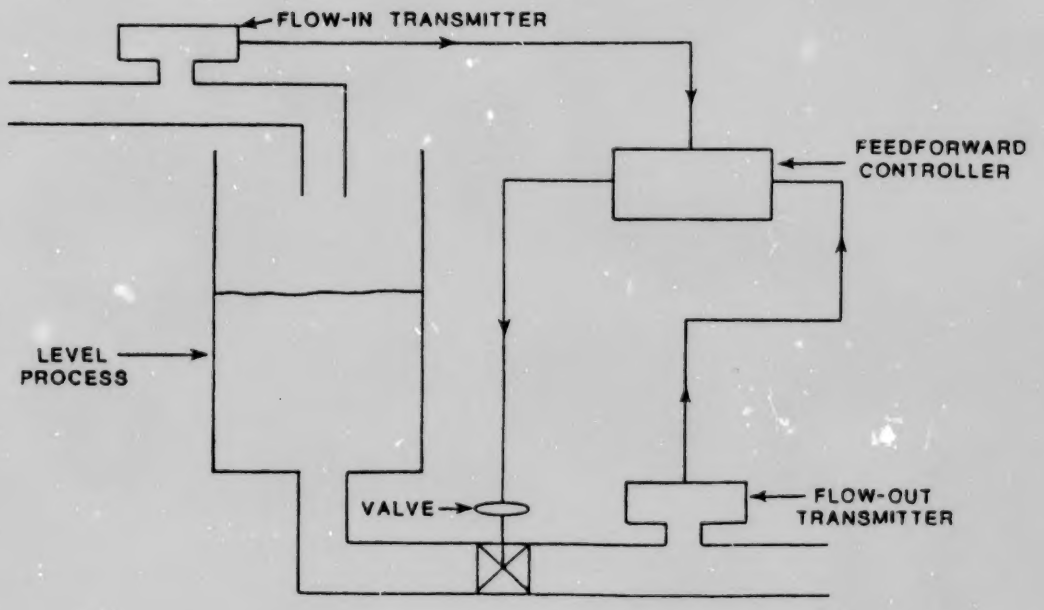



Figure 33-1-11. Block diagram of a feedforward level control process.

Processes and process components are easier to understand when represented by block diagrams. Most industrial facilities require generation of steam, which is accomplished by a boiler. The simplest representation of a boiler is given in Figure 33-1-12. This diagram represents a major system that signifies that water and heat energy generate steam. The major systems can be broken down into smaller subsystems for clarity.

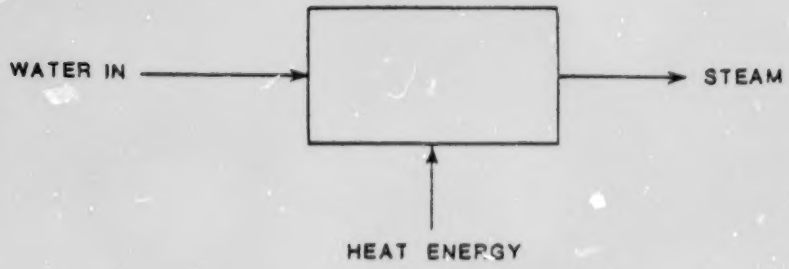



Figure 33-1-12. A steam boiler.

Although industrial boilers are of many different types and designs, they all require that water flows into them at the same rate that steam leaves them. In other words, a pound of water is required to generate a pound of steam. The fuel also must be controlled at an exact rate in order that just enough heat energy is added to convert the water to steam and to elevate the saturated steam by addition of pressure. A block diagram of a boiler and some basic control systems is provided in Figure 33-1-13.

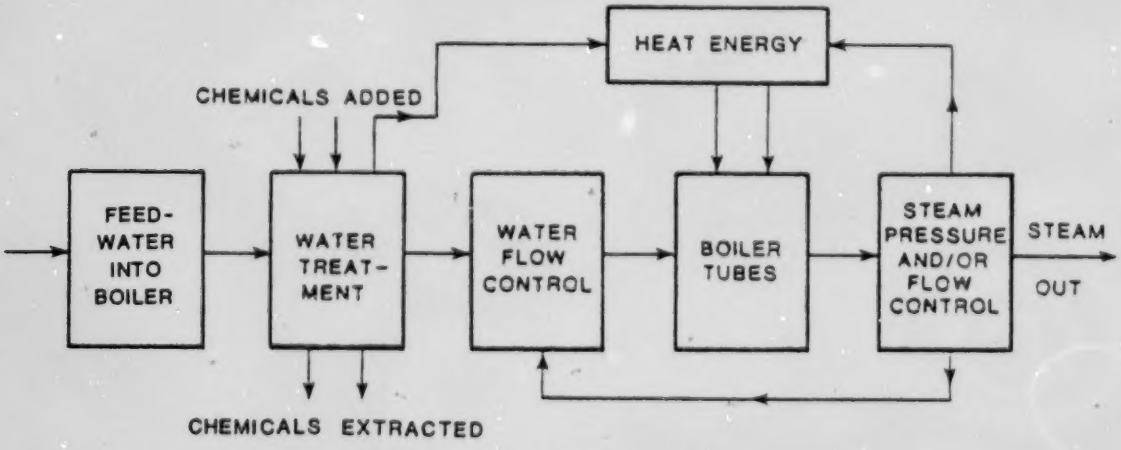



Figure 33-1-13. Steam boiler block diagram.

The diagram in Figure 33-1-13 indicates that water enters the boiler and that chemicals are added and extracted for chemical treatment of the boiler feedwater. The flow of water is controlled in accordance with the steam demand upon the boiler. As steam demand increases, causing an increase in steam flow, the signal from the steam-control system is routed to the water-flow control system to prevent the boiler tubes from being flooded with water or becoming empty. Heat energy is applied to the boiler tubes as a function of water and/or steam flow. The addition of heat energy requires additional subsystems to position rods in a nuclear reactor or to control the combination of fuel and combustion air flow for conventional fuel boilers.

Each of the component blocks shown in the diagram could be further divided into subsystems. The chemical addition and flow control of water, steam, and fuel would be subsystems simlar to the feedback closed-loop control system in Figure 33-1-10. Fuel control for conventional fuel boilers also would consist of feedback flow loops with the possible use of cascade, ratio, or feedforward control systems. These combinational control systems will be detailed in later modules of this series.

The boiler diagram could be represented as a single block in the representation of an entire manufacturing plant or facility. An example is shown in Figure 33-1-14. Arrows in the back direction from the voltage control center to the generator, to the turbine, and finally to the boiler, indicate that the control of each stage is dependent upon the following stage. An increase in demand for electricity would cause the voltage to decrease and cause the generator load to increase, slowing down the generator. When turbine speed decreases, a speed-control governor increases steam

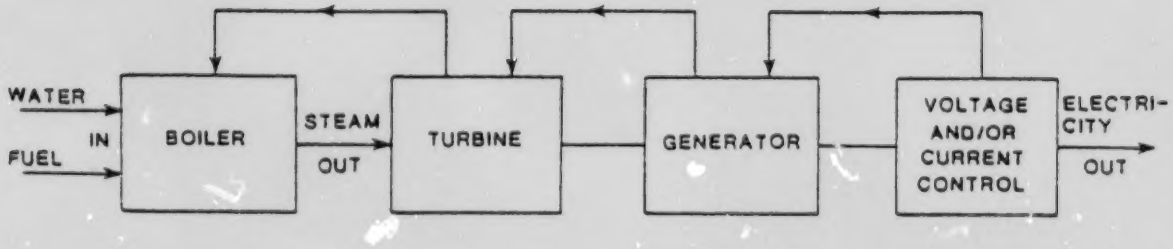



Figure 33-1-14. An electrical power generating plant.

flow to the turbine, which increases demand on the boiler. Increased demand on the boiler causes an increase in steam flow and/or a decrease in steam pressure. In order to meet such increased demand, the boiler control system must add more fuel to the boiler to generate more steam. Thus, an increase in power out of the plant requires an increase in fuel into the plant. The entire plant can be depicted as one block whose function is to convert heat energy to electrical energy (Figure 33-1-15).

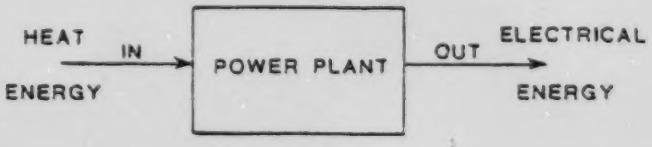



Figure 33-1-15. A power plant.

In most of the examples given in the explanation of the use of block diagrams, large systems were developed from smaller subsystems. Sometimes, a designer's approach is more helpful because it develops subsystems from large

complex systems. This technique will be used to describe an alarm system for a boiler. The alarm system in Figure 33-1-16 is designed to provide an audible sound and a flashing light on any of the following conditions:

- Low feedwater flow.
- High steam pressure.
- High steam temperature.

The simplest block diagram would depict these subsystems as in Figure 33-1-16.

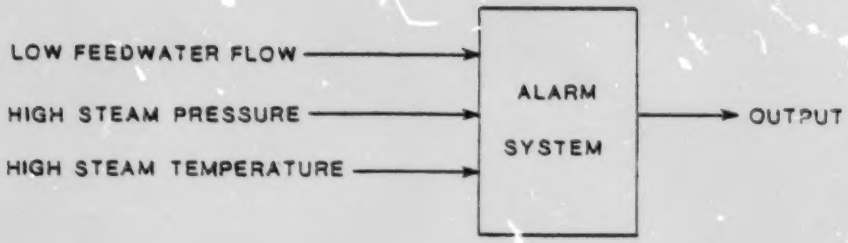



Figure 33-1-16. A three-input alarm system.

To show more detail, the system can be divided into subsystems (Figure 33-1-17). The subsystems could be divided still further to show the types of process sensors, the means by which the sensor outputs are detected, the means by which sound and light are produced, etc. The actual operation of the individual components normally is not revealed by block diagrams. The purpose of block diagrams is to define the function provided by the components.

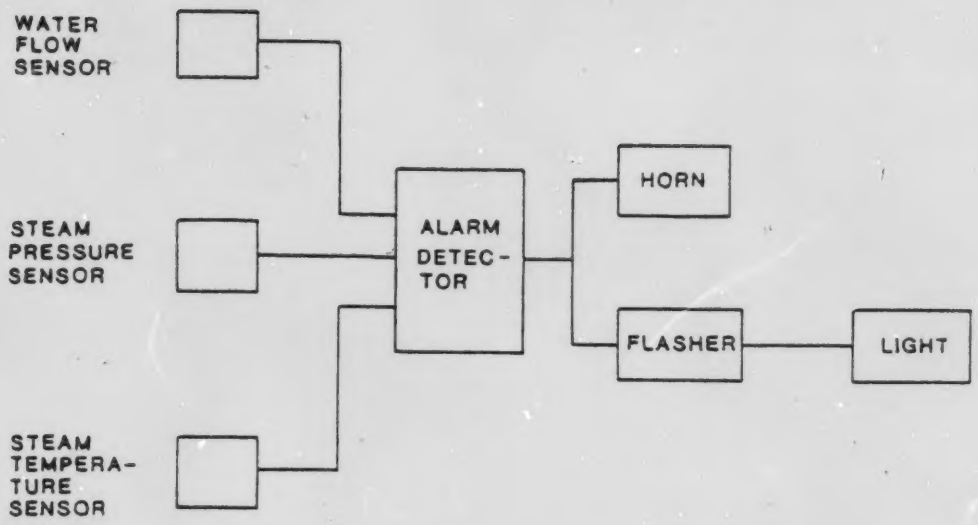



Figure 33-1-17. A three-input alarm system with subsystems.

In order to become familiar with the system approach to processes, several common processes should be illustrated in block diagram form. The components, or "black boxes," should be listed with explanations of the functions they provide. An understanding of the complete system should be verified by stating its operation.

## EXERCISES

Draw block diagrams of the following systems, showing components; and explain component and system operation.

1. A closed-loop control process.
2. A flashlight.
3. A home heating system. (This is most likely a closed-loop system for temperature control.)
4. An open-loop control system likely to be found around the home.
5. The drive train of an automobile.

## MATERIALS

None.

## PROCEDURES

None.

## DATA TABLES

None.

# REFERENCE MATERIALS

Anderson, Norman A. Instrumentation for Process Measurement and Control. 2nd Ed. Philadelphia: Chilton Co., 1972.

Bateson, Robert. Introduction to Control System Technology. 8th Ed. Columbus, OH: Charles E. Merrill Publishing Co., 1973.

Considine, Douglas M. Process Instruments and Controls Handbook. 2nd ed. New York: McGraw-Hill Book Company, 1974.

1. Define the following terms:
   a. Closed-loop control.

   b. Open-loop control.

   c. Feedback control.

   d. Feedforward control.

   e. Transfer function.

2. List major disadvantages of a closed-loop control system.

3. What is the difference between the transfer function of an amplifier and that of a controller?

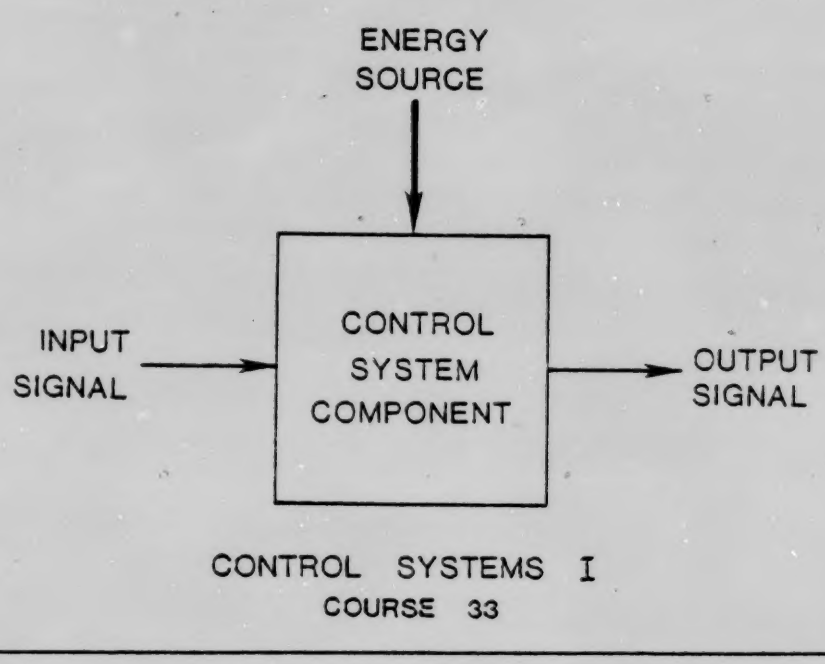
4. What provides the feedback link in a closed-loop system?

5. Why is process measurement unnecessary in a feed-forward control system?

# NUCLEAR TECHNOLOGY

## MODULE 33-2

INPUT / OUTPUT DEVICES




CONTROL SYSTEMS I
COURSE 33

ORD CENTER FOR OCCUPATIONAL RESEARCH AND DEVELOPMENT

CONTENTS

COURSE 33 CONTROL SYSTEMS I


MODULE 33-1 Introduction to Block Diagrams
MODULE 33-2 Input/Output Devices
MODULE 33-3 Control System Theory
MODULE 33-4 Pneumatic Control Mechanisms
MODULE 33-5 Control Valves
MODULE 33-6 Process Control Characteristics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# INTRODUCTION

Control applications in nuclear and conventional facilities require the measurement of process variables. Most measurements are inferential in nature, necessitating the transformation of energy from one form to another. Transducers are input/output devices that measure process variables and that convert information about the variables into another form.

The operation of all technical systems requires that information about those systems be made available to some controlling mechanism. An automobile, for example, may contain gages that indicate speed, fuel level, oil pressure, and temperature. Each of these gages is connected to a device called a "transducer." The transducer converts information about the conditions in the automobile into a signal transmitted to the gage, where it is displayed.

Transducers, then, are devices that accept an input signal containing information in one energy system (engine temperature, for example) and convert it into an output signal containing the same information in another energy system (displacement of a needle on a calibrated scale).

# MODULE PREREQUISITES

The student should have completed Course 3, "Principles of Process Instrumentation"; Course 4, "Heat Transfer and Fluid Flow"; Course 6, "Instrumentation and Control of Reactors and Plant Systems"; and Module 33-1, "Introduction to Block Diagrams."

# OBJECTIVES

Upon completion of this module, the student should be able to:

1. Define the term "transducer."
2. Explain transducer operation.
3. Define the term "sensor."
4. Explain the operation of the following devices used as transducers or sensors:
   - Linear variable differential transformer (LVDT).
   - Potentiometer.
   - Variable inductor.
   - Variable capacitor.
   - Synchros.
   - Flyball governor.
   - Motors used as generators.
   - Bonded strain gages.
   - Pressure elements.
   - Thermocouples.
   - Resistance temperature device (RTD).
5. Explain the principle of the following pressure measurements by use of one of the transducers listed in Objective 4.
   - Fluid flow.
   - Temperature.
   - Liquid level.
   - Pressure.
   - Angular rotation.
6. Perform calibration procedures by which the proper input-output relationship is established for the following process measurement devices:
   - Flow transmitter.
   - Temperature transmitter.
   - Level transmitter.

7. Explain the difference between measurement for local and remote applications.

Before a variable can be controlled, it first must be measured. A simple illustration will establish the importance of this concept. To control the speed of an automobile, the operator must be able to determine the speed. When a driver encounters a speed-limit warning sign, the first impulse is to glance at the speedometer. If the indicated speed is greater than that permitted, the driver will release pressure on the accelerator to allow the speed to decrease. Without knowledge of how fast the automobile is traveling, the driver could not maintain the desired speed. It can be said, however, that speed control can be accomplished without the aid of a speedometer. In such cases, the driver relies upon intuitive evaluation to judge the present speed. Therefore, measurement is still preliminary to actual control techniques.

In the control of processes in nuclear power plants, reliance upon intuitive measurements and measurement speculation could produce disastrous results. For this reason, instruments are provided to ascertain correct and accurate process conditions. These measuring instruments utilize transducers. Transducers are physical hardware components designed to transform proportionally the information that exists in one energy system to that in another energy system. Simply stated, a transducer converts one form of energy to another form of energy. By doing so, an indication or measurement signal which represents the condition of the median being observed is produced.

## SENSORS

The term "sensor" has been used interchangeably with transducer, but there is a major difference in application between the two terms. A sensor is a transducer used to measure the condition of a process and to provide an input to the process control system. The sensor measures the condition of the process under control and converts this information into an energy system of a more usable form.

In the discussion of sensors, it is important that one understands the input and output functions provided. The block diagram in Figure 33-2-1 describes the function of all sensors – to receive energy from a source, then to act on that energy in such a manner as to provide transformation of the input energy to a more usable form of energy that is available at the output.

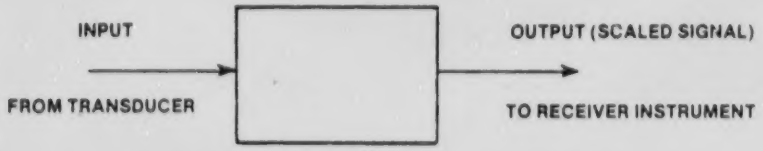



Figure 33-2-1. Block diagram of a sensor.

Table 33-2-1 lists the input-output relationship and describes the transfer function of various transducers. It should be noted that outputs are not necessarily generated by the transducer but, rather, a change in output.

Sensor inputs are derived from the process under measurement, and the outputs provide the intelligence response from which the measurement is derived. Although the output of some of the sensors may produce information in a usable

TABLE 33-2-1. INPUT-OUTPUT RELATIONSHIPS FOR VARIOUS TRANSDUCERS.

| Transducer | Input | Output | Transfer Function |
|---|---|---|---|
| Potentiometer | Linear or rotary motion | Resistance | Motion to resistance |
| LVDT | Linear motion | Voltage | Motion to voltage |
| Inductor | Linear or rotary motion | Inductance | Motion to inductance |
| Capacitor | Linear or rotary motion | Capacitance | Motion to capacitance |
| Flyball governor | Rotary motion | Force | Motion to force |
| Strain gage | Force | Resistance | Force to resistance |
| Pressure element | Force | Movement (motion) | Force to motion |
| Thermocouple | Heat | Voltage | Heat to voltage |
| RTD | Heat | Resistance | Heat to resistance |
| Synchros | Rotary motion | Current | Motion to current |
| Thermistor | Heat | Resistance | Heat to resistance |

form, others must be refined somewhat for meaningful data. Sensors that produce electrical quantities such as resistance and capacitance must be accompanied by additional circuitry before they can produce usable information. Of course, the electrical quantities can be measured with an electrical test instrument; however, the output must be in a more usable form. The following discussion and examples will demonstrate the means by which outputs are converted to more usable energy forms.

## THE WHEATSTONE RESISTANCE BRIDGE

The transducers in Table 33-2-1 which have resistance outputs most commonly will be connected to a bridge circuit. A change in the measured variable will result in a change in resistance measured by a bridge circuit. A bridge circuit similar to that in Figure 33-2-2 is utilized in the measurement of resistance.

$R_1$ and $R_2$ are ratio resistors that help to determine bridge sensitivity. The variable resistor $R_3$ establishes initial bridge balance when $R_4$ is at the reference value. $R_4$ is the variable resistance output of the transducer and changes with the variable to be measured. The dotted lines indicate that the resistor is a part of the transducer. The transducer input is a variable, as listed in Table 33-2-1.

Many electronic measuring and recording devices contain bridge circuits. Bridge balance, the condition that exists when the voltage at the millivolt recorder is zero, occurs when the conditions presented by Equation 33-2-1 are met.

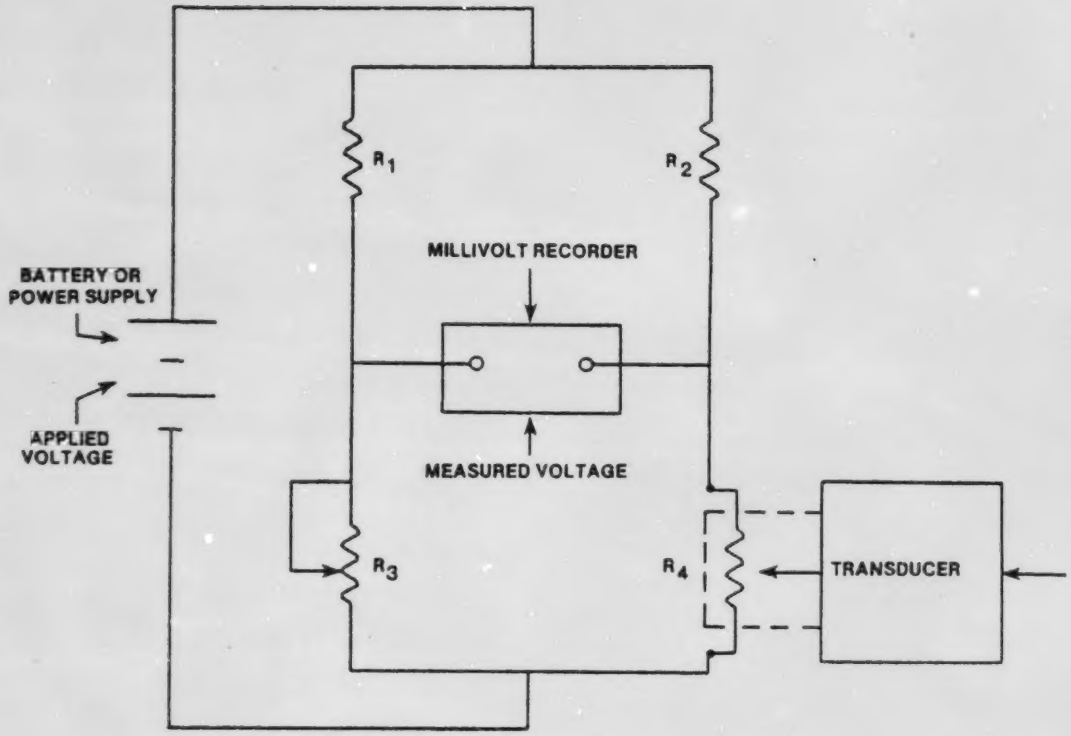



Figure 33-2-2. A bridge circuit for resistance measurement.

$$\frac{R_1}{R_3} = \frac{R_2}{R_4} \quad \text{or} \quad R_4 = \frac{R_2}{R_1}(R_3) \qquad \text{Equation 33-2-1}$$

(Equation = Eq.)

The voltage at the millivolt recorder is determined by Equation 33-2-2.

$$E_x = E_a \left[\frac{R_1}{R_1 + R_3} - \frac{R_2}{R_2 + R_4}\right] \qquad \text{Eq. 33-2-2}$$

where:

$R_1$, $R_2$, $R_3$, and $R_4$ are as described in Figure 33-2-2.

$E_x$ = bridge unbalance voltage at the recorder.

$E_a$ = applied bridge voltage of the battery or power supply.

The change in the value of $R_4$ with a change in the measured variable is the important consideration in this type of measurement. A device that produces a change in resistance with a change in temperature (RTD) would be connected to the bridge circuit as designated by $R_4$. The RTD can be represented by a black box in a block diagram as in Figure 33-2-3.

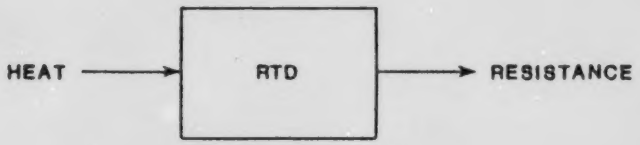



Figure 33-2-3. Block diagram of RTD.

The transfer function of the RTD is established by the design and manufacture of the device. The relationship between heat and resistance probably will be nonlinear and will be furnished by the supplier in either table or graph form. The gain of the RTD can be listed as resistance change divided by temperature change, and will vary with temperature range because of the nonlinearity of the device.

The following example illustrates the principle of temperature measurement by RTD.

EXAMPLE

Given:

1. An RTD produces 0.5 ohm change in resistance for each 1°F change in temperature and is at 500 ohms at 60°F. This is a safe assumption for a small temperature range. For large temperature ranges, this relationship will change because of the nonlinearity of the device. Bridge circuit components would be used in practical applications to correct for the nonlinearity. The resistance value of the RTD is represented as $R_4$ in Figure 33-2-2.
2. $R_1 = R_2 = 1$ k ohm.
3. $E_a = 20$ volts.
4. $R_3$ is a variable resistor with values from 0 to 1000 ohms. It is set at 500 ohms to balance the bridge when the temperature of the RTD is 60°F, at which time its resistance is 500 ohms.

Find: The unbalance bridge voltage when the temperature of the RTD is 62°F.

Solution: From Equation 33-2-2

$$E_x = 20\ V\ \left(\frac{1000}{1000 + 500}\right) - \left(\frac{1000}{1000 + 500 + 1}\right)$$

$$= 20\ V\ \left(\frac{1000}{1500}\right) - \left(\frac{1000}{1501}\right)$$

$$= 20\ V\ (0.6666667 - 0.6662225)$$

$$= 20\ V\ (0.0004442)$$

$$E_x = 0.00888\ V = 8.88\ mV.$$

If the temperature in this example had decreased by 2° to 58°F, the voltage value would have been negative. Normally, a reference point is established, and all temperature measurements are made in one direction from the reference point. If all temperature measurements are made above 60°F for the application illustrated in the example, the voltage read at the recorder will always be positive. Temperature change above and below a reference point can be made when a voltage recorder that can measure both positive- and negative-going voltages is used. Such devices are called "center zero" instruments because the reference temperature that produces initial bridge balance results in a recorder response at the center of the instrument scale. Figure 33-2-4 shows the scale for a center-zero instrument. At a temperature of 20°F, the pointer would be at the extreme left position; but a temperature of 100°F would cause the pointer to move to the extreme right position. The temperature-measuring range of the instrument would be 20°F to 100°F.

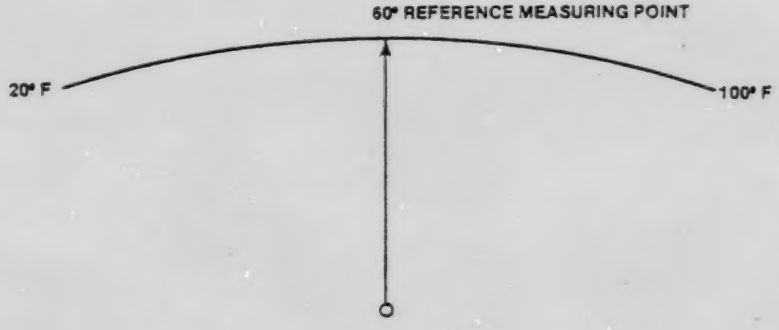



Figure 33-2-4. Center zero instrument.

When an RTD transducer that provides a transfer function of temperature to resistance is connected to a bridge circuit

as shown in Figure 33-2-1, temperature can be measured as a function of voltage. The total arrangement of bridge circuit and temperature transducer is a temperature sensor. The transfer function of the sensor is temperature to voltage.

The relationship between temperature and voltage is established by calibration, which can be accomplished by voltage values calculated for different values of temperature. The corresponding temperature values are marked off on the voltage-recorder scale; then a direct temperature reading can be made. The recorder then is said to be a temperature recorder, although it still responds to an unbalanced bridge voltage caused by a temperature change at the RTD.

All the transducers in Table 33-2-1 that have resistance, inductance, or capacitance outputs can be employed with bridge circuits to provide measurements. The inductance and capacitance values are impedance quantities and must be incorporated into an a.c. bridge network.

In a nuclear plant, the recorder of a temperature sensor usually is located in a control room; and the transducer and other associated components comprise a temperature transmitter that generates the voltage signal from a remote location. Figure 33-2-5 is a block diagram of a temperature-measuring system: The transmitter (sensor) and receiving instrument (recorder) are represented.

When the input to a transducer is a linear or rotary motion, that transducer normally is used with another transducer that converts force quantities to motion. Most force-to-motion transducers are pressure elements, the most common of which are covered in Module 3-6, "Principles of Process

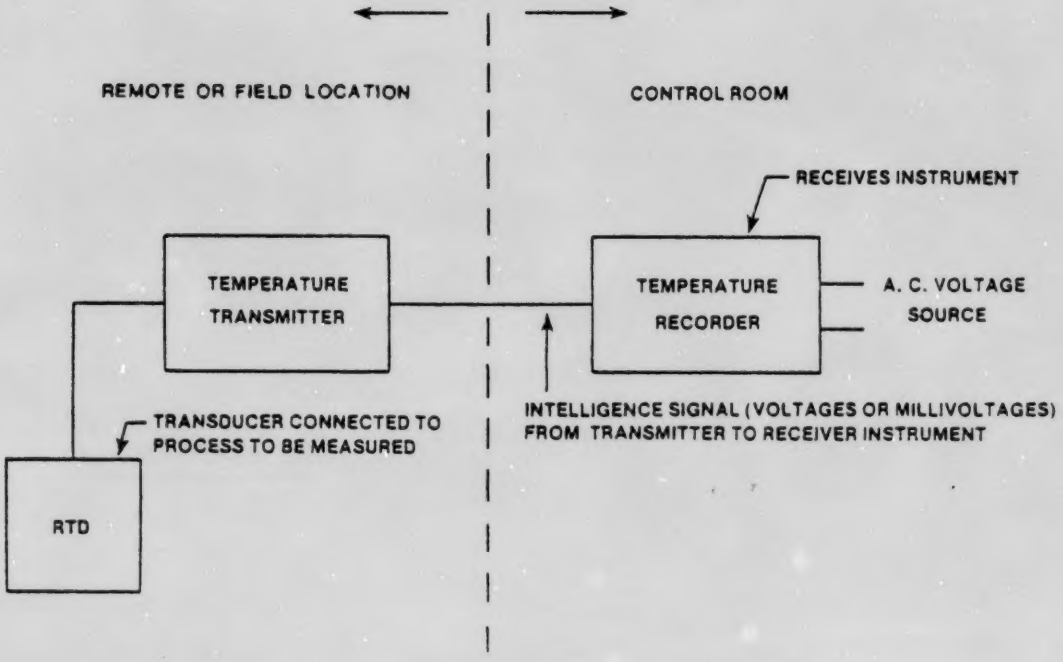



Figure 33-2-5. Block diagram of a temperature-measuring system.

Instrumentation." Motion produced by the pressure element is converted to an electrical or pneumatic signal by one of the transducers listed in Table 33-2-1.

## LINEAR VARIABLE DIFFERENTIAL TRANSFORMER

The LVDT probably is the most common type of transducer used to convert motion to a change in voltage. By proper application of this device, force quantities are converted to usable voltage and current signals. A transformer is utilized to transform energy from one coil (primary winding)

to another (secondary winding). The amount of energy transformed between the two coils is determined by the position of a movable iron core located between the two windings. Movement of the core can be as small as a few ten-thousandths of an inch or as large as six to eight inches. An LVDT is shown schematically in Figure 33-2-6.

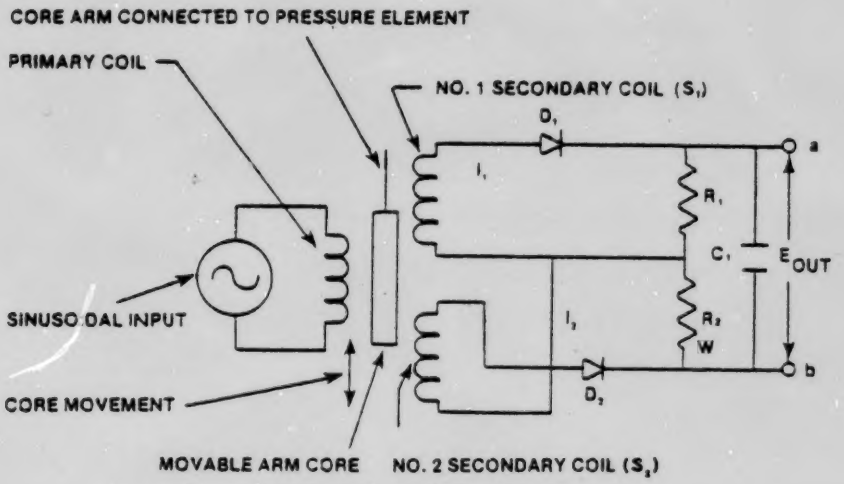



Figure 33-2-6. LVDT and signal conditioning circuit.

The secondary coils are as electrically and mechanically identical as possible. When the core is centered electrically between $S_1$ and $S_2$, $I_1$ will equal $I_2$; and the voltage drop across $R_1$ is equal to $R_2$, but opposite in polarity. The voltage between points a and b ($E_{out}$) is then zero.

When the core is positioned closer to $S_1$ than to $S_2$, $I_1$ is greater than $I_2$ because of the increase in mutual inductance between the primary coil and $S_1$. The voltage drop across $R_1$ is greater than that of $R_2$, and point a then will be more positive than point b. An output voltage will

develop because point a is positive with respect to point b.

If the core is positioned closer to $S_2$, then $I_2$ will be greater than $I_1$; the voltage drop across $R_2$ will exceed that of $R_1$; and point a will be negative with respect to point b. The output voltage developed between a and b will be negative. The polarity of the output voltage is determined by the position of the iron core with respect to $S_1$ and $S_2$ and indicates the direction of the core movement from the center position.

The voltage levels just described are for the positive half of the sinusoidal input. On the negative half cycle, the currents $I_1$ and $I_2$ reverse direction and are blocked by the diodes $D_1$ and $D_2$. No current flows through resistors $R_1$ and $R_2$, and no voltage develops at the output terminals a and b.

The electrical output will be half-wave rectified a.c., and capacitor $C_1$ across the output terminals will produce a bipolar d.c. voltage. This is the output voltage.

The output of the LVDT just described depends upon the characteristics and physical location of the secondary coils relative to each other. As previously mentioned, they must have identical electrical and mechanical characteristics. The output characteristics are dependent upon the excitation frequency and voltage level. This frequency normally is controlled by an oscillator circuit contained in instruments which use the LVDT. Examples of such instruments will be given later in this module.

## LINEAR-MOTION VARIABLE INDUCTOR

C tubes and bellows produce more relative motion than other pressure elements. Where C tubes and bellows are used as force-to-motion transducers, a linear-motion variable inductor can be employed to convert the motion to an electrical measurement, as depicted in Figure 33-2-7. Figure 33-2-8 is a schematic of a linear-motion variable inductor.

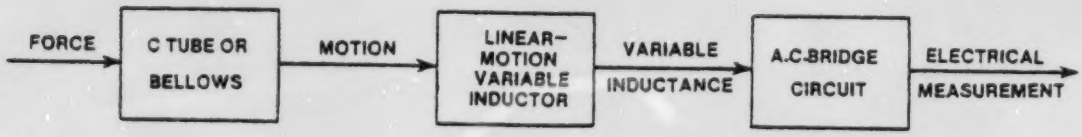



Figure 33-2-7. Linear-motion variable inductor application.

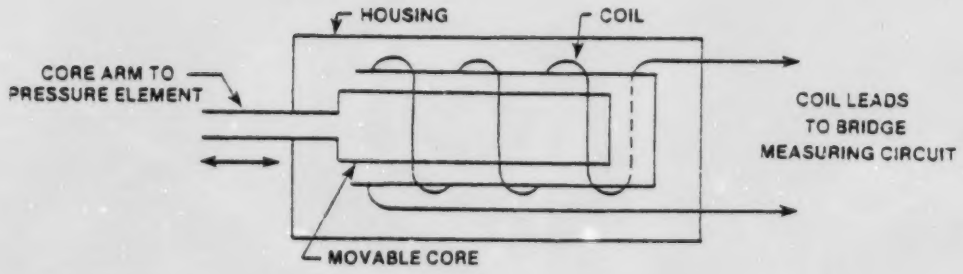



Figure 33-2-8. Linear-motion variable inductor.

The movement of the core caused by force on the pressure element produces a change in the inductance of the coil. Change in inductance results in an unbalance of the a.c.

bridge circuit, which produces a voltage that is a function of the force. The operation is very similar to that of the d.c. resistance bridge described earlier.

## LINEAR-MOTION POTENTIOMETER

The linear-motion potentiometer shown in Figure 33-2-9 requires about the same amount of movement from the pressure element as a variable inductor, but has the disadvantage of requiring more force to overcome its greater friction. Linear-motion resistors are utilized with d.c. bridge circuits to produce voltage or current outputs.

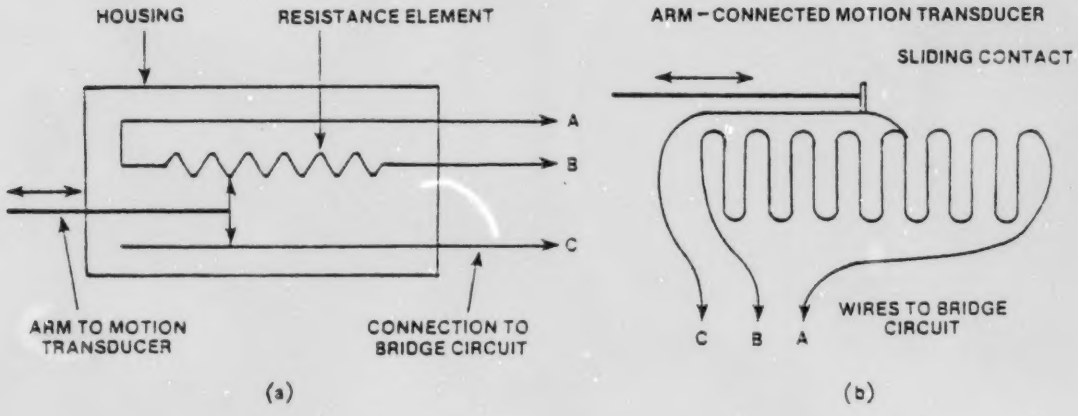



Figure 33-2-9. Linear-motion potentiometer.

As the arm moves along the axes (shown by the arrows in Figure 33-2-9), the resistance is varied between wires A and C and B and C. This change in resistance, when connected to a bridge circuit, causes an unbalanced voltage that changes the response of a recorder. The linear poten-

tiometer in Figure 33-2-9b has greater resolution than the one in Figure 33-2-9a; therefore, the smaller amounts of movement can be detected for a given amount of resistance. Less friction on the wiper contact also increases precision, but the device is more susceptible to damage.

## THERMISTORS

Thermistors are semiconductor devices that produce a resistance change with a change in temperature. They have an advantage over the RTD mentioned earlier because they are much more sensitive to temperature changes. They are more likely to be damaged by excessive current and are more fragile. They have found extensive use where maximum temperature sensitivity is required. Like other resistive devices, they are used with bridge circuits.

## THERMOCOUPLES

Thermocouples transfer heat energy directly into electrical energy. The use of bridge circuits is unnecessary in the conversion of transducer output to a usable form. Thus, thermocouples provide a very convenient means of energy transformation. A block diagram of a typical thermocouple measuring system is given in Figure 33-2-10.

The thermocouple output is a function of the temperature difference between the reference and measuring junctions and is detected by a millivolt recorder. The recorder output is calibrated for a convenient temperature scale. Reference-junction compensation is achieved by electrical circuits usually located in the recorder.

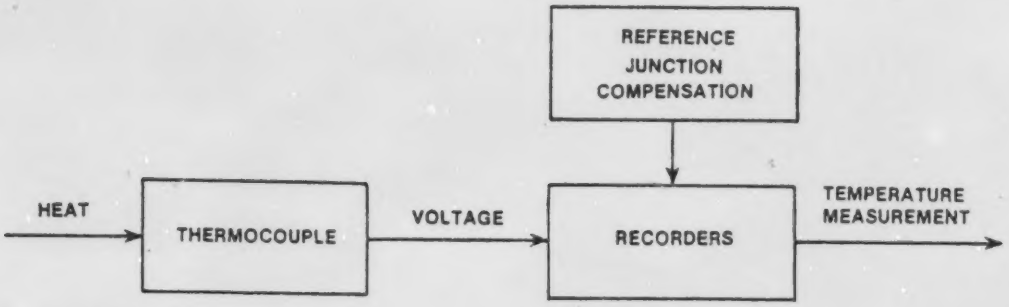



Figure 33-2-10. Block diagram of thermocouple measuring system.

The relationship between voltage and temperature is non-linear and available from companies that manufacture thermocouple equipment. This information has been derived empirically and is available for thermocouple types commonly used in nuclear installations.

## PROCESS MEASUREMENT DEVICES (TRANSMITTERS)

Process variable measurements necessary for nuclear power plant operators are –

- Liquid level.
- Temperature.
- Fluid flow.
- Pressure.

All of these variables are measured by transducers previously discussed in this module. Table 33-2-2 lists transducers used for various measurement applications.

In practical application, process measurement is made in the field or at actual process locations. An intelligence

signal is generated from the transducer response to a process change and sent to a receiving instrument, normally located in a control room. (Refer to Figure 33-2-5 for a block-diagram representation of a measuring system.) In receiving instruments, transducers transform energy from the intelligence signal into motion. This motion drives a pen arm on a recorder or controller.

TABLE 33-2-2. TRANSDUCERS USED FOR PROCESS VARIABLE MEASUREMENT.

| Liquid Level | Fluid Flow | Temperature | Pressure |
|---|---|---|---|
| Pressure element<br>"C" tube<br>Diaphragm<br>Bellows<br>Spiral<br>Linear motion<br>Variable impedance<br>Variable resistance<br>Strain gage<br>Floats and displacers<br>LVDT<br>Flapper and nozzle<br>Ultrasonic device<br>Electrodes<br>Radioactive source and detector | Pressure elements<br>Diaphragm<br>EMF generation<br>Magnetic flow meters<br>Rotary motion<br>Turbine meters<br>LVDT<br>Flapper and nozzle<br>Variable capacitance<br>Ultrasonic detector | RTD<br>Thermistors<br>Thermocouple<br>Pressure element<br>Optical pyrometers<br>Flapper and nozzle | Pressure element<br>Strain gage<br>LVDT<br>Flapper and nozzle<br>Variable capacitance |

LEVEL MEASUREMENT

Table 33-2-2 indicates that many different types of transducers are used for level measurements. The most common level measurement applications utilize a pressure element that converts the force from a hydrostatic head of liquid into motion. The motion produced by the pressure element is converted to an electrical or pneumatic intelligence signal for transmission. Figure 33-2-11 is a schematic of a level measuring system that utilizes a pressure transducer and linear-motion variable resistor. The linear-motion variable inductor, capacitor, flapper nozzle, or any of the transducers for level measurement in Table 33-2-2 can provide the input to a level sensor.

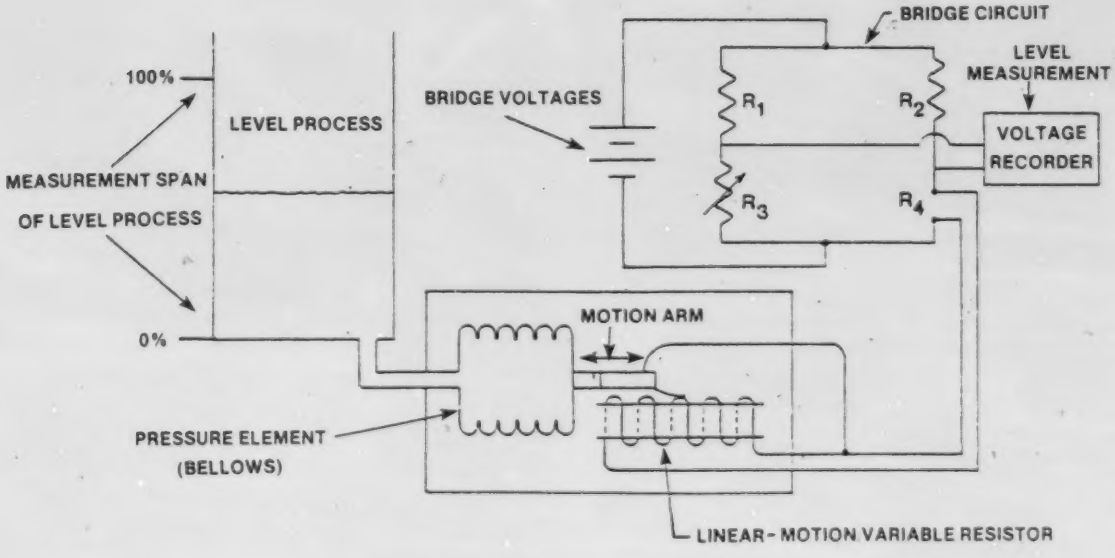



Figure 33-2-11. Pressure transducer, variable resistor and bridge circuit used for level measurement.

The system in Figure 33-2-11 is typical of those for level measurement. The hydrostatic head of liquid in the tank exerts a pressure on the bellows. The bellows expands and contracts as the level increases and decreases, and the resulting motion causes a contact to slide across the variable resistor that changes the resistance value. The bridge circuit is sensitive to changes in resistance and produces a voltage that corresponds to the level variations.

A general representation of level measurement is presented by the block diagram in Figure 33-2-12. The pressure element responds to pressure variations and pressure is related to liquid level by Equation 33-2-3.

$$p = h\ (0.433)(G) \qquad \text{Eq. 33-2-3}$$

where:

h = height of the level in feet.
G = specific gravity of the liquid.
$p$ = pressure in pounds per square inch (psi).

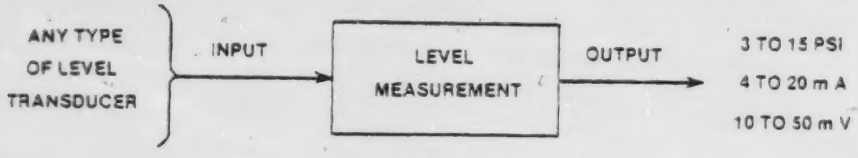



Figure 33-2-12. Block representation of level transmitter.

The ranges of most level measuring instruments are stated as receiving inputs in inches of water instead of

pounds/sq in and as generating an output signal that corresponds to a standard range. The output signals of most instruments are as follows:

- 3 to 15 psi.
- 4 to 20 milliamps.
- 10 to 50 millivolts.

A differential pressure measuring sensor (d/p cell) provides a very popular means of level measurement. A metallic capsule or diaphragm functions as a transducer that flexes slightly when different pressures are applied to each side. An LVDT or flapper-nozzle arrangement converts the movement to a convenient electrical or pneumatic signal for transmission to a receiving instrument. Figure 33-2-13 shows a d/p cell transmitter.

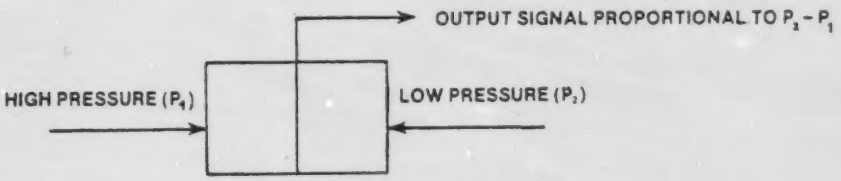



Figure 33-2-13. A d/p cell.

When the tank is empty, all the static pressure inside it is applied to both sides of the d/p cell. The output signal from the transmitter is zero percent – 3 psi, 4 mA or 10 mV – because there is no difference in the pressure. As the level in the tank increases, pressure on the high-pressure side of the d/p cell increases because of the hydrostatic head of the liquid. (The relationship between pressure and hydrostatic head is explained by Equation 33-2-3.)

The d/p cell responds to this increase in level as an increase in pressure and generates an output proportional to level gain.

The impact on a level transmitter as shown in Figure 33-2-12 can be from any of the transducers listed in Table 33-2-2, and the output can be any of those given. A pressure element can generate movement in a moving coil of an LVDT to produce a voltage proportional to level change (Figure 33-2-14). When level transmitters are represented as black boxes, the type of transducer employed is of little significance. What is important is that a change in liquid level on the input causes a corresponding output signal. The relationship between input and output is established during instrument calibration.

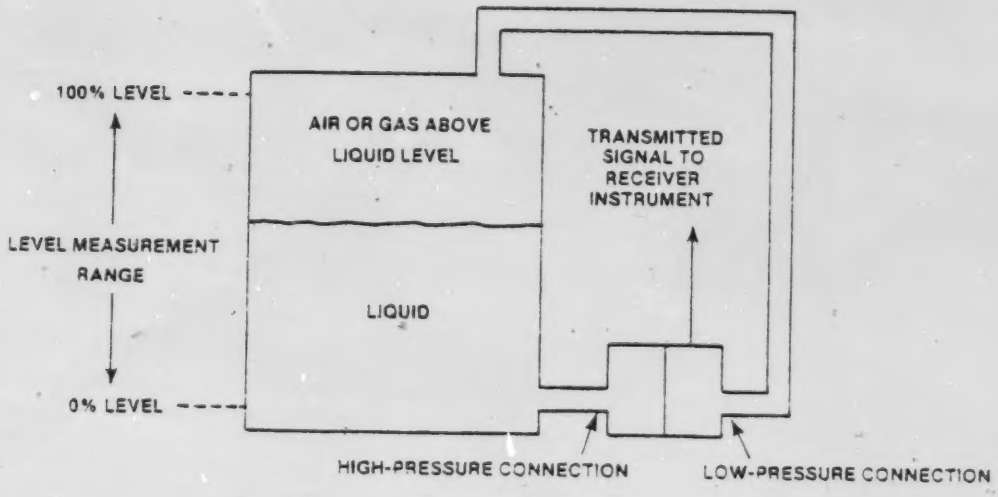



Figure 33-2-14. Level measurement with d/p cell.

Floats and displacers provide a simple means of level measurement. Floats are employed for visual level indication, but are not used as tranducers to generate signals for transmission because of the great amount of movement produced. The interface of two liquids with different densities is measured with displacers. The displacer level-measurement system in Figure 33-2-15 measures the interface of oil and water.

When the displacer chamber is full of oil, the apparent weight of the displacer is less than when it is full of water. The difference in weight caused by different buoyance effects of the liquids produces a movement of the motion arm.

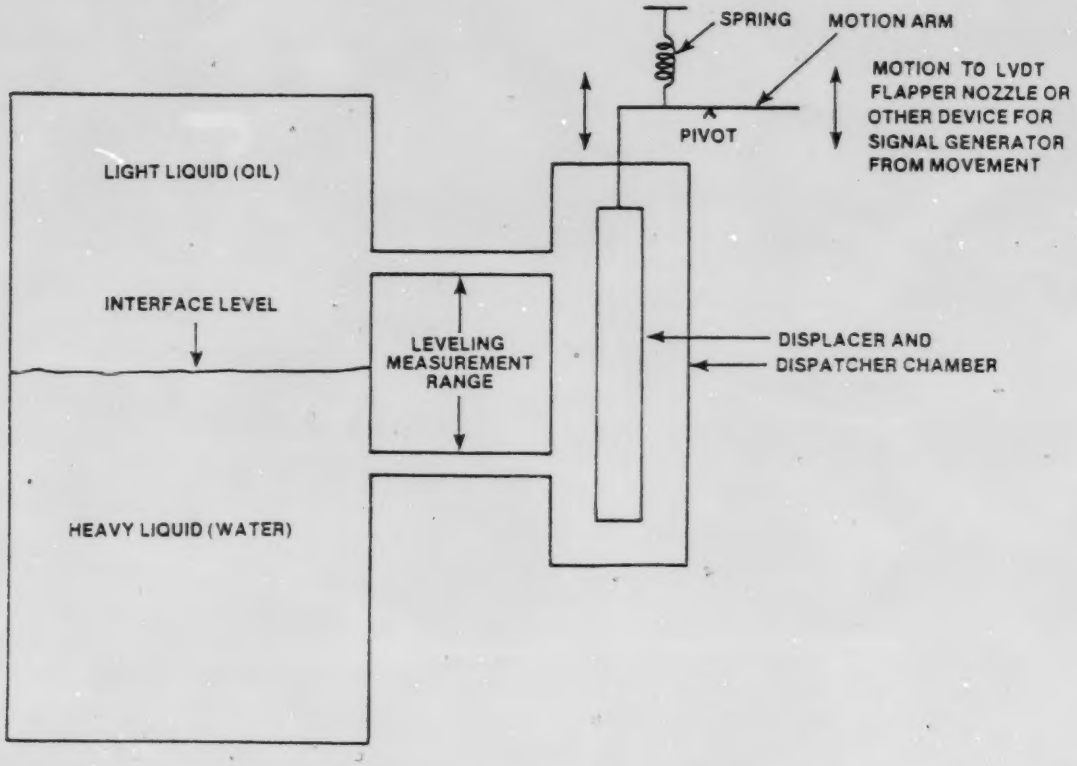



Figure 33-2-15. Level measurement with displacers.

The motion arm is connected to an intelligence signal for transmission.

## FLUID FLOW

Fluid flow meters are divided into two large categories: They are called "head type," or differential producing type, and "nonhead type." The most common is the head type, so called because a restriction is placed in the line and produces a pressure (head) drop. This pressure drop increases the fluid velocity (flow), as illustrated in Figure 33-2-16.

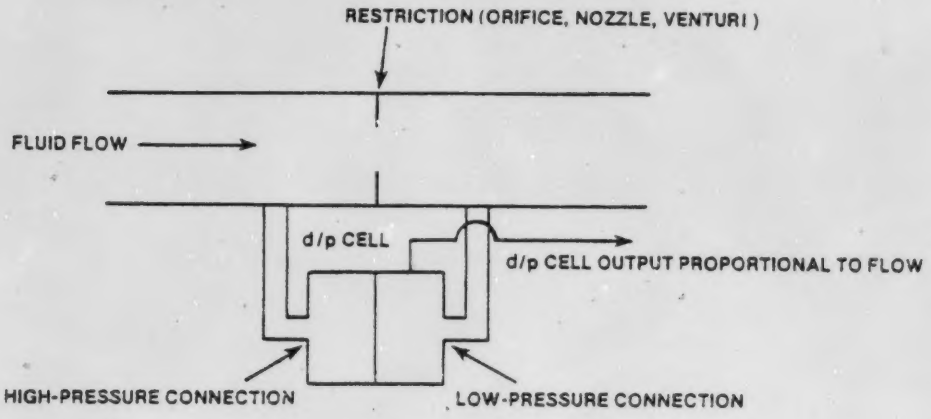



Figure 33-2-16. A d/p cell used for flow measurement.

The relationship between differential pressure and flow rate is expressed by Equation 33-2-4.

$$Q = kA\sqrt{d/p} \qquad \text{Eq. 33-2-4}$$

where:

Q = flow rate.

k = constant that depends upon restrictor, fluid characteristics, and physical properties of the flow loop.

d/p = differential pressure developed across the differential producer (restrictor) caused by the flowing fluid.

Calibrations required to convert differential pressure to actual flow quantities are complex in nature and are covered in Module 3-7, "Flow-Sensing Devices: Differential-Pressure Flowmeters," of this series.

Head type flow meters commonly are used in power plants to measure –

- Steam flow.
- Boiler feedwater flow.
- Air flow.
- Wastewater flow.
- Cooling water flow.

## STRAIN GAGE MEASUREMENT

Strain gages are devices (wires or other metal conductors) that change resistance values when they undergo tension variations. The block diagram in Figure 33-2-17 indicates that the input to a strain gage is force converted to a resistance change (output).

Figure 33-2-17. Block diagram of a strain gage.

Strain-gage applications once were limited to high-pressure and force measurement but now are becoming more prominent in conventional types of pressure transmitters. The strain gage in Figure 33-2-18 is of the typical bonded-wire type. An increase in pressure causes the retaining container to expand, stretching the wire and causing it to change resistance. The resistance change is detected by a bridge circuit, which produces an electrical output of voltage or current.

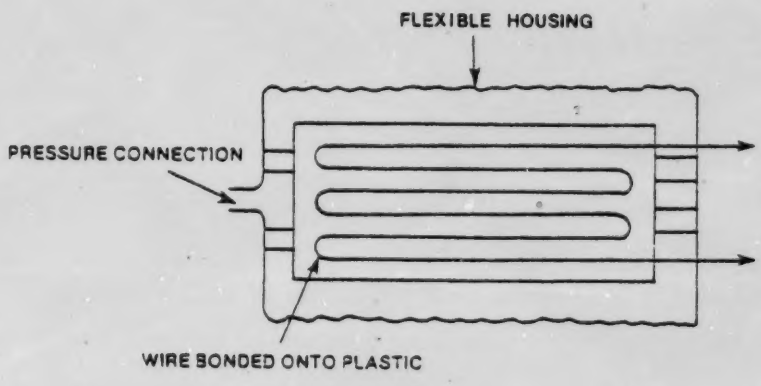



Figure 33-2-18. Bonded strain gage.

When pressure is applied to the strain gage, the bellows expands, causing the plastic bonded to the housing to become distorted (stretched). This process causes a deformation of the wire, which results in a change of length and cross-sectional area. Because the resistance of a wire is a function of cross-sectional area and length, it will undergo a resistance change.

TACHOMETERS

Small a.c. and d.c. generators are employed in the measurement of compressors, turbines, and other rotating equipment in power plants (Figure 33-2-19). The output of a generator is a function of the speed of rotation if all other variables are held constant. The output (normally voltage), which is directly proportional to the speed of rotation, is converted to revolutions per minute or to a standard unit of angular rate-of-motion. The relationship between input and output is established by empirical calibration.

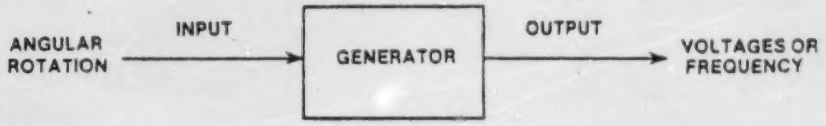



Figure 33-2-19. A generator used as a tachometer.

All process measurement devices require the transformation of energy from one form to another. The transformation usually is in two stages. First, a measurement variable is converted to motion. The motion (except in the case of pressure gages used for local indication) then is transformed to a conveniently scaled signal. The signal is transmitted to a receiver instrument, where another transformation of energy converts the signal into a recording indication for read-out purposes.

Pressure measurement applications are very similar to those discussed for flow and level measurement. The pressure to be measured is applied to a pressure element

that generates a movement. The movement then generates a scaled signal. Obviously, the measurement of any variable requires transformation of energy to a usable form. Transducers and active elements, such as flapper-nozzle arrangements and electronic amplifiers, are utilized for this purpose.

## EXERCISES

1. Show by drawing and explanation how the following measurements are made:
   a. Liquid level to produce a scaled voltage signal.
   b. Fluid flow to produce a scaled pneumatic signal.
      Hint: Review the principles of flapper-nozzle operation in Module 3-7, "Flow-Sensing Devices: Differential-Pressure Flowmeters."
   c. Force and pressure measurement to produce a scaled voltage signal.
   d. Temperature measurement to produce a voltage measurement.
2. Draw a bridge circuit for the measurement of resistance. Identify and explain the purpose of all components.
3. For the bridge circuit in Exercise 2, find the bridge unbalance voltages.
   Given: a. The ratio resistors are 1000 ohms each.
   b. The variable resistor to provide initial bridge balance is adjustable between 0 and 1000 ohms.
   c. An RTD changes 2 ohms for each 12°F temperature change and is at a value of 500 ohms at 60°F.

d. Initial condition is a balanced bridge when the RTD is at 60°F.

e. Find the bridge unbalance voltage when the temperature is 56°F, 58°F, 62°F, and 64°F.

## MATERIALS

A pneumatic d/p cell equipped with an adjustable input range (approximate) of 0 to 200 inches of water.

Instruction manual for d/p cell.

Test instrument to generate and to measure the input signal. This instrument can consist of a pressure regulator employed with a pressure gage or a manometer to read inches of water.

Test instrument with which to measure the output. This instrument can be a pressure gage or manometer to read psi.

A d/p cell with which to measure level or flow. This instrument can be either electronic or pneumatic, with an adjustable input range (approximate) of 0 to 200 inches of water.

Instruction manual for the d/p cell.

Test instruments with which to generate and measure input signal. These instruments can be a pressure regulator and a pressure gage or a manometer.

Test instruments with which to measure the output. These can consist of a pressure gage for pneumatic instruments and a Volt-Ohm-Milliammeter (VOM), with appropriate scales, for the electronic d/p cell.

1. Connect the equipment as shown in Figure 33-2-20. Refer to the instruction manual for connection identification. Block valves 1 and 2 should be closed at the time.

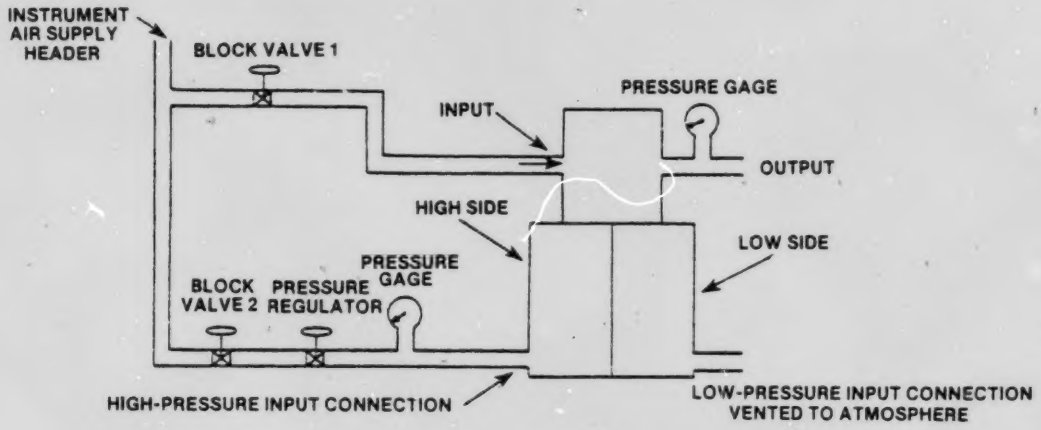



Figure 33-2-20. A d/p cell calibration setup.

2. Adjust pressure regulator for minimum pressure by turning the adjustment wheel counterclockwise.
3. Open block valve 1, which will apply air to the instrument.
4. Locate range adjustment; set it to 100 inches of water as displayed on the range indicator.
5. Open block valve 2; adjust pressure regulator until the value indicated on the input pressure gage is 100% of the input range. The output pressure gage reads 15 psi.
6. With equal pressure on both sides of the d/p-cell diaphragm (this is atmospheric pressure because the low side is vented, and because supply to the high side is blocked), make adjustments to the zero adjust screw until the output is zero percent, or 3 psi.

7. If output reaches 100%, 15 psi, before input is 100% (100 inches), the input range is too low and must be increased. If output reaches 100% after input is 100%, the range is too high and must be decreased. Note the range adjustment needed to obtain proper input range.
8. Reduce pressure in the input with the pressure regulators until output is zero; make the range adjustment as determined in Step 7.
9. Repeat Step 4.
10. Increase pressure on the input with the pressure regulator until output is 100%.
11. Repeat Step 7.
12. Repeat Step 8.
13. Repeat Steps 9, 10, 11, and 12 until the following relationship is established:

| Input | Output |
|---|---|
| 0% (0 inches) | 0% (3 psi) |
| 100% (100 inches) | 100% (15 psi) |

The instrument is now calibrated for 0 and 100%. Accuracy checks for mid-scale values now should be made.

14. To determine mid-scale accuracy, determine input and output values for increments of 10%; and complete Data Table 33-2-1 by taking readings of corresponding inputs and outputs.
15. Determine the percent error for each 10% increment by the following equation:

$$\% \text{ error} = \frac{\text{true value} - \text{measured value}}{\text{true value}} (100)$$

16. The error should be no greater than that specified in instrument specifications. If it is, refer to the instrument instruction manual for steps to be taken.

The preceding calibration procedure is general in nature because it establishes the proper input-output relationship for the instrument under test. The same general procedures can be used to calibrate any instrument. Such procedures must include the following steps:

- Assimilate the process conditions. This was accomplished with the pressure regulator.
- Measure assimilated conditions. The input pressure gage was used for this purpose.
- Determine the corresponding input and output relationships. This is done in Data Table 33-2-1.
- Make proper zero and range adjustments until the proper input-output relationship is determined.

The qualified technician can calibrate any device by following procedures as set forth in the instrument service manual and by adhering to the principles listed above.

# DATA TABLE

DATA TABLE 33-2-1

INPUT/OUTPUT RELATIONSHIP OF d/p CELL.

| Percent | Input Inches | Output psi | | Percent Error |
|---|---|---|---|---|
| | | Actual | Measured | |
| 0 | 0 | 3.0 | | |
| 10 | 10 | 4.2 | | |
| 20 | 20 | 5.4 | | |
| 30 | 30 | 6.6 | | |
| 40 | 40 | 7.8 | | |
| 50 | 50 | 9.0 | | |
| 60 | 60 | 10.2 | | |
| 70 | 70 | 11.4 | | |
| 80 | 80 | 12.6 | | |
| 90 | 90 | 13.8 | | |
| 100 | 100 | 15.0 | | |

# REFERENCE MATERIALS

Hunter, Ronald P. Automated Process Control Systems Concepts and Hardware. Englewood Cliffs, NJ: Prentice-Hall, 1978.

O'Higgins, Patrick T. Basic Instrumentation Industrial Measurement. New York: McGraw-Hill Book Co., 1966.

University of Texas Petroleum Extension Services. Basic Instrumentation. 2nd ed. Austin, TX; University of Texas Press, 1964.

1. Define the following terms:
   a. Transducer.

   b. Sensor.

   c. Transmitter.

   d. Receiver instrument.

2. List the common scaled signal ranges for the following:
   a. Pneumatic transmitters.

   b. Electronic transmitters (current).

   c. Electronic transmitters (voltage).

3. Explain how the following devices are used in instrument sensors:

   a. Pressure element.

   b. LVDT.

   c. RTD.

   d. Thermistors.

   e. Thermocouples.

4. Explain the purpose of a Wheatstone bridge circuit in process variable measurements.

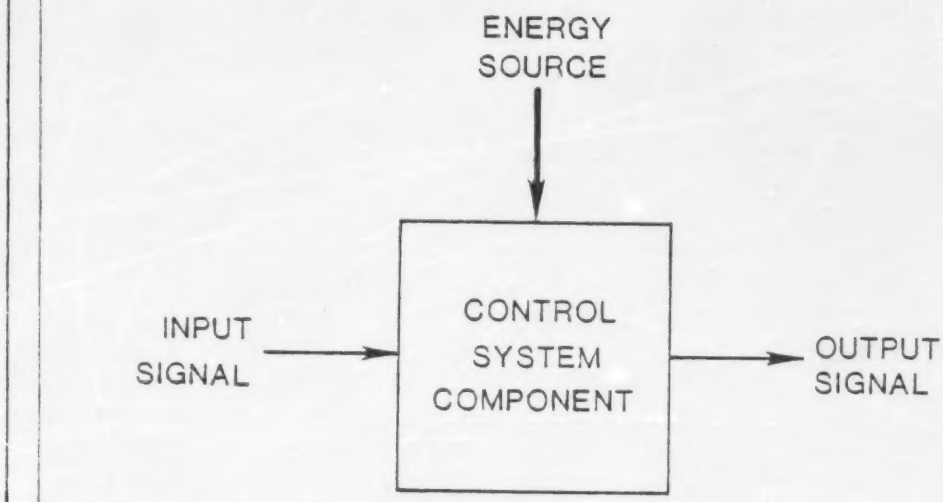
5. Explain the principle of level measurement with a d/p cell.

6. Explain the principle of flow measurement with a d/p cell.

# NUCLEAR TECHNOLOGY

## MODULE 33-3

CONTROL SYSTEMS THEORY




CONTROL SYSTEMS I
COURSE 33

ORD CENTER FOR OCCUPATIONAL RESEARCH AND DEVELOPMENT

CONTENTS

COURSE 33 CONTROL SYSTEMS I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| MODULE 33-5 | Control Valves |
| MODULE 33-6 | Process Control Characteristics |


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# INTRODUCTION

The successful operation of industrial plants is highly dependent upon the automatic control of many process variables. These variables determine plant safety, product quality control and efficient utilization of resources. Relief from drudgery has been the motivating force behind the development of many control-system applications; at least, during the early development stages. The obvious advantages derived from the reduction of drudgery alone would not warrant the care taken in the establishment of the present degree of process-control optimization. Mainly, the desire to produce more goods of the highest quality in the most efficient manner has spawned the field of control-system technology.

The purpose of this module is to familiarize the student with control system theory and to discuss the methods and operations by which processes are controlled automatically. The dynamic behavior of process and control elements used in the automatic mode will be covered.

# MODULE PREREQUISITES

The student should have completed Course 3, "Principles of Process Instrumentation"; Module 33-1, "Introduction to Block Diagrams"; and Module 33-2, "Input/Output Devices."

# OBJECTIVES

Upon completion of this module, the student should be able to:

1. Define the following terms:
   - Process.
   - Process control.
   - Disturbance variable.
   - Process gain.
   - Process capacitance.
   - Process variable.
   - Manipulated variable.
   - Negative feedback.
2. State the objectives of a control system.
3. Discuss operating characteristics of a process in terms of load changes.
4. Describe the relationship between disturbance variables, process stability, and process characteristics.
5. Demonstrate the two following process characteristics by use of a process electropneumatic trainer:
   - Flow.
   - Liquid level.

## CONTROL-SYSTEM TERMINOLOGY

Before the nature of systems and their capacity to be controlled can be understood, the terms defined below must be mastered:

- A process is that which is to be controlled. The most common types of processes encountered in nuclear power facilities are –
  - Liquid level.
  - Fluid flow.
  - Pressure.
  - Temperature.
- Process control is the technique by which prescribed process conditions are maintained.
- Disturbance variables (load changes) are conditions that, when altered, will influence the value or condition of a process.
- Process variables (measured variables) are process quantities that must be measured or controlled. For a level process, the level or a signal proportional to, and representing the level, is the process variable.
- Process gain is the ratio of process output to process input. Process output is the process variable. Process input is the manipulated variable:

$$\text{Process gain} = \frac{\text{Process output}}{\text{Process input}}$$

- Manipulated variable is the controlled medium that adds energy or material to the process to maintain process conditions.

- Process capacitance is the energy or material storage ability of the process.
- Dead time is time required for a process to react to a change in input. This input can result from a change in disturbance variable or a change in control-valve position.
- Lag time refers to the time required for instruments to respond to a process change or time required for signal transmission from one instrument to another.

The objective of any control system is to maintain a balance between the supply and demand on the process at a desired point. The majority of control systems are automatic, which means that control is accomplished by instruments without the need for individual attention. Figure 33-3-1 is a diagram of a closed-loop system. (The terms employed in Figure 33-3-1 are defined under the next heading.)

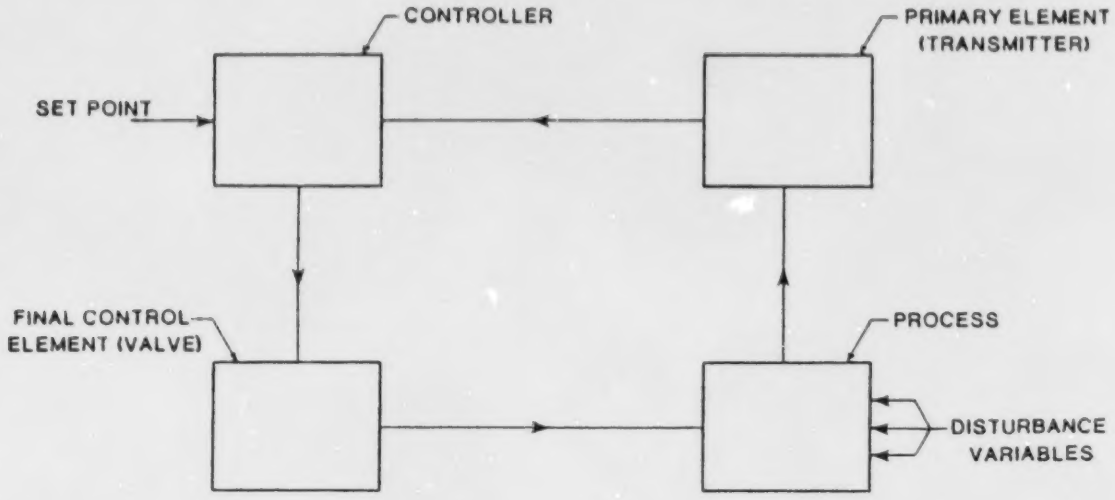


Figure 33-3-1. A closed-loop control system.

## TERMINOLOGY FOR THE CLOSED-LOOP SYSTEM IN FIGURE 33-3-1

### Process

The process in Figure 33-3-1 could be a tank in which the level of a liquid must be controlled.

### Primary Element

The primary element is a level-measuring device that monitors the process conditions (level). It generates a signal proportional to the level and transmits the signal to a controller.

### Controller

The controller is the decision-making component of the system. It receives a signal, which is significant to the process conditions, from the transmitter. The "set point" is the condition at which the process is to be controlled and normally is established by the process operator.

### Final Control Element

The final control element receives a transmitted signal from the controller and controls the manipulated variable. In this case, the final control element is a valve whose degree of opening is determined by the controller.

The block diagram in Figure 33-3-1 illustrates the arrangement and interconnection of the components necessary for a control system. Regardless of the type of process to be controlled, all the components are required, and their function will be as described.

## CONTROL-SYSTEM OPERATION

In the control system represented by Figure 33-3-2, the level in the vessel is controlled by the position of the valve that controls the flow of water into the tank. (Remember that the purpose of a control system is to maintain a balance between supply and demand on a process at a desired point.) If the flow of water (the supply) into the tank is made equal to the water leaving the tank (the demand), the level will be controlled. The controller performs this equalizing function.

All the components in Figure 33-3-1 are displayed more descriptively in Figure 33-3-2. The final control element regulates the amount of flow into the tank; and the level transmitter provides measurement by any conventional means. The controller generates an output that is a function of the difference between the signal from the level transmitter and the set point value. An algebraic summer, which usually is an integral part of the controller, provides the difference measurement. The final control element is positioned by the signal from the controller and regulates the flow into the process.

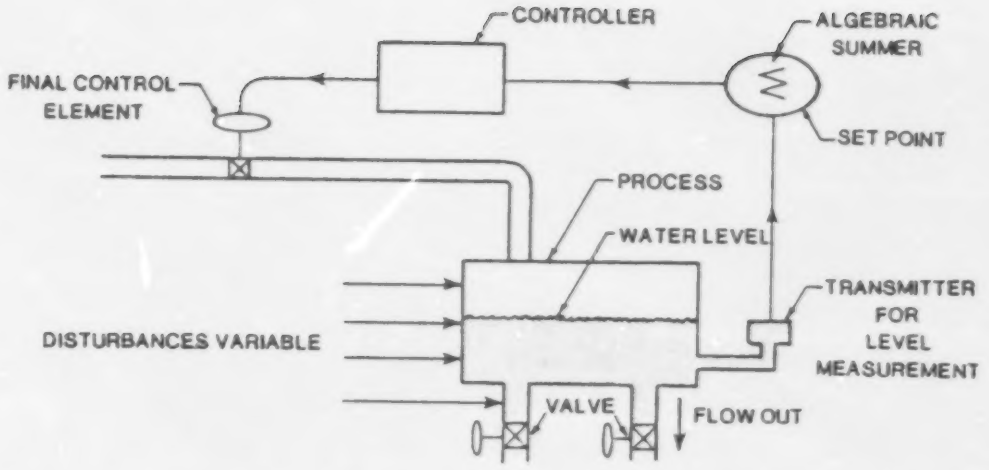


Figure 33-3-2. A closed-loop system for the control of level.

DISTURBANCE VARIABLE

The "disturbance variables" are any variations, controlled or "wild" (uncontrolled), that can cause the level to change. Examples of disturbance variables are variations in flow out of the tank caused by drain valves, uncontrolled flow entering the tank, or even changes in environmental conditions such as rain or temperature. Disturbance variables normally are called "load changes" on the process and are critical to the operation of control systems; in fact, if it were not for load changes on processes, automatic control could not be justified. Consider, for example, that if the flow out of the tank in Figure 33-3-2 and all other disturbance variables were constant, the valve that regulates flow into the tank could be set manually

at a position to maintain the inlet flow at a rate equal to the outlet flow, thus maintaining a constant level and negating the need for an automatic control system.

Because process loads do vary from time to time and other disturbance variables are unpredictable, automatic feedback control is necessary. Assume that initially the flow into the tank depicted in Figure 33-3-2 is equal to the flow out. The level then is stable at a desired value. When a load change on the process occurs, the flow out is increased; consequently, the level will decrease because the flow in no longer is equal to the flow out.

When the control system is under automatic control, the decrease in level will be detected by the transmitter. The decrease in the signal at the controller input will result in a proportional change in controller output. The change in controller output, in turn, will position the valve open to increase the flow into the tank in such a manner that a new balance between supply and demand will be established.

The foregoing description of the operation of an automatic control system is oversimplified, and a number of system operating characteristics need further clarification. Components of the control system exhibit characteristics that must be matched to provide process control. The process itself has characteristics that must be compatible with the instruments in order that safe and stable operation can be provided.

## FAIL-SAFE OPERATION

Control systems are designed to be "fail safe." This means that in circumstances resulting from a loss of instruments or instrument control signals, the process will fail in a condition that is nonhazardous to equipment and personnel. In the process depicted in Figure 33-3-2, the decision must be made to cause the level to fail either high or low, as desired. If a hazardous condition exists when the level is too high, the system should be designed such that it will fail low. If, conversely, a hazardous condition exists when the tank is empty, the system should fail high. There are also some cases in which it is desirable for the system to fail as is; for example, to lock a final control element in the event of loss of air pressure to a system or process. This decision will determine the valve operation and controller action.

## VALVE OPERATION

Control valves for process control are classified as either "signal-to-open" or "signal-to-close." A signal-to-open valve (also known as "normally closed") will return to, and stay in, the closed position when a loss of signal occurs. On the other hand, a signal-to-close valve (also known as "normally open") will return to, and stay in, the open position upon a loss of signal. The choice of control-valve mode of operation will cause the process to fail in a safe condition. In the process of Figure 33-3-2, a signal-to-open valve will cause the tank to fail empty; and a signal-to-close valve will cause the tank to fail full.

## CONTROLLER ACTION

Upon receipt of an increased transmitter signal (process variable), a controller will respond in one of two different modes of operation: either as a direct-acting controller, or as a reverse-acting controller. A direct-acting controller will produce an increased output with an increase in process variable; whereas, a reverse-acting controller will produce a decreased output with an increase in process variable. The controller action should be selected with the process requirements in mind. Specifically, the controller should be selected to provide a negative feedback on the process in question.

## NEGATIVE FEEDBACK

In a negative-feedback control system, the controller output must be such that the controller signal's effect on the final control element causes an action on the process that is opposite in effect to the process disturbance that produced the change in controller output. Consequently, selection of a controller action will depend upon the nature of the system's fail-safe parameters, which determine the type of valve operation that will be selected.

Once the valve operation has been chosen, the controller action will be selected. If the tank in Figure 33-3-? is required to fail empty, the valve should be signaled to open. When the level decreases as a result of change in load, the process variable signal will decrease. This decreasing signal must cause the valve to open in order to stop the decrease in level. The signaling of the valve

to open will require an increase in signal from the controller. A decrease in process variable must cause an increase in controller output, and the controller must be "reverse acting."

If the tank in Figure 33-3-2 is required to fail full or high, the valve for this application must fail open and must be signal-to-close type. For the controller to provide negative feedback to the process and to cause the valve to close on increasing level, the controller action must be "direct acting." An increase in process variable will produce an increase in controller output that will close the valve.

Another process will be given here to expound upon the concept of valve selection for fail-safe operation and controller action to provide negative feedback. Figure 33-3-3 illustrates another level process. The valve on this process controls the level by regulating the flow of water out of the tank.

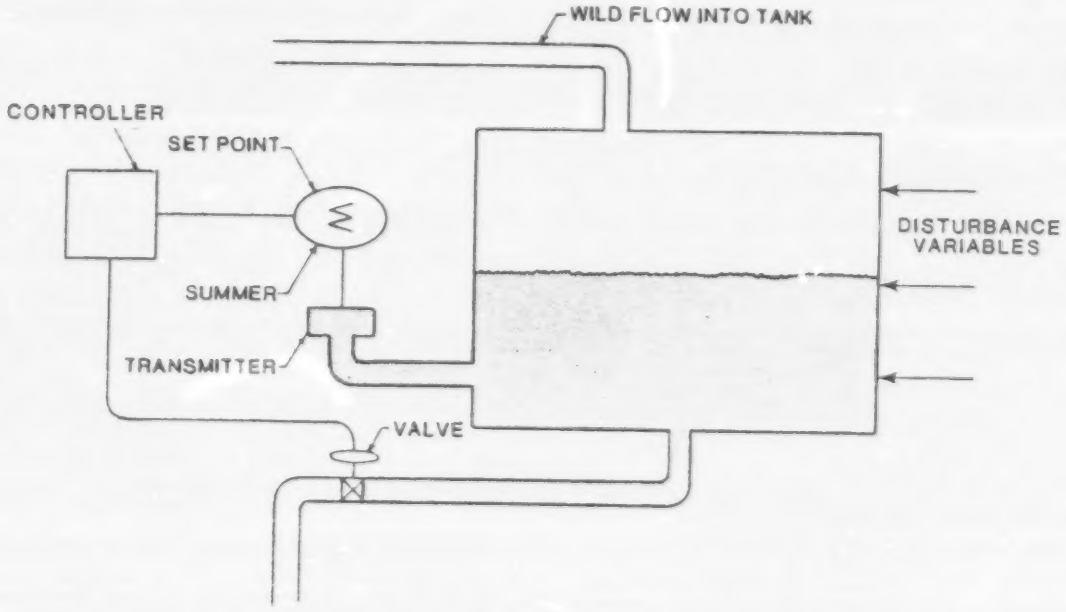


Figure 33-3-3. A level process.

By reasoning already established, the controller action and valve operation will be selected for fail-safe operation. First, if the level should fail low, the valve should fail open; therefore, the valve should be signaled to close. For an increase in process variable, the valve should open to allow more water to leave the tank. The controller then must be reverse acting. An increase in process variable causes a decrease in controller output, which opens the signal-to-close valve.

If the tank is required to fail full, the valve must fail closed or signal to open. An increase in process variable must cause the valve to open, requiring a decrease in signal. The controller then must be direct acting.

Table 33-3-1 lists the valve operation and controller action for the processes in Figure 33-3-2 and 33-3-3 for both fail-high and fail-low conditions. The terms "A/O" and "A/C" often are used to mean "air-to-open" and "air-to-close," respectively, for control valves. Although most control valves, even for electronic control loops, are air- or pneumatically-operated, the terms sometimes signify the operation of electrically-operated valves. The expressions "signal-to-close" or "signal-to-open" also can be employed.

TABLE 33-3-1.

VALVE OPERATION AND CONTROLLER ACTION FOR PROCESSES IN FIGURES 33-3-2 AND 33-3-3.

| | Process in Figure 33-3-2 | | Process in Figure 33-3-3 | |
|---|---|---|---|---|
| | Fail High | Fail Low | Fail High | Fail Low |
| Valve Operation | signal to close | signal to open | signal to open | signal to close |
| Controller Action | direct acting | reverse acting | direct acting | reverse acting |

## DYNAMIC PROPERTIES OF PROCESSES

Now that the principle of control systems and control-system operation has been established, the concept of process dynamics and the relationship between process dynamics and control-system dynamics must be presented. The only means of controlling a process is through regulation of the final control element (valve) by the controller. The control should be such that energy and/or material must be added to the process at an amount and rate to which the process can respond.

The phrase "process dynamics" describes a process reaction to a load change. One should remember that load changes require automatic control. Consider the speed control of an automobile. On a straight, level section of highway, the accelerator can be held in one position, and the automobile speed will be constant. Energy (the flow of gasoline into the carburetor) is being added at a constant rate. The rate at which the energy is being added is just equal

to the amount needed to maintain a constant speed. The automobile neither is accelerating nor decelerating. When the load is increased, by an incline in the highway or other reason, the automobile will slow down. To maintain a constant rate of speed, the flow of fuel must add energy to the automobile at a rate to which the automobile can respond. This rate depends upon the particular automobile. A large truck pulling a heavy load can absorb a tremendous amount of energy, and a great amount of energy will be required to cause the truck to accelerate. Proper acceleration is accomplished by a large engine and the ability to regulate a comparatively large amount of fuel flow to the engine. The same arrangement would produce great acceleration rates for a compact automobile.

Just as in the example of the compact automobile and large truck with a heavy load, processes respond to load changes and added energy at different rates. Consider, for example, the two level processes in Figure 33-3-4 and 33-3-5.

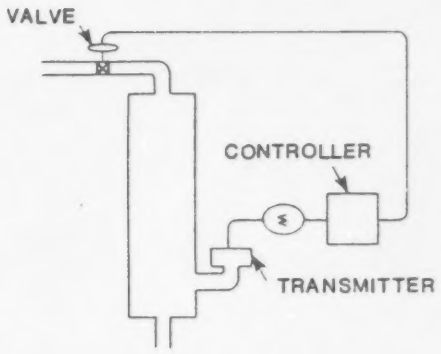


Figure 33-3-4. Level process with high capacitance.

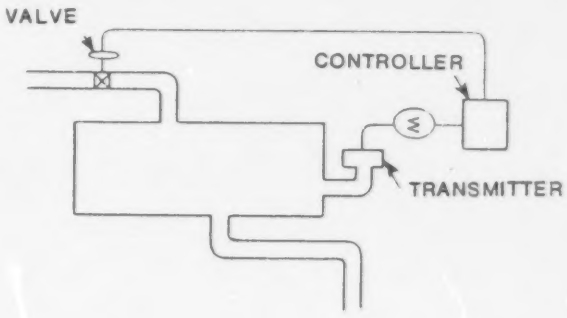


Figure 33-3-5. Level process with low capacitance.

## ENERGY STORED IN PROCESSES

The tanks in Figures 33-3-4 and 33-3-5 could have the same capacity; that is, they could retain the same amount of liquid in gallons or other units of liquid measurement. For the purpose of level measurement (which is a linear measurement in feet, inches, or another unit of length), the dynamic characteristics are completely different. The term "capacitance" is used better to describe the dynamic properties of a level process. Capacitance is measured in $\frac{\text{foot}}{\text{gallon}}$, which relates the level (length) measurement to volumetric measurement. The capacitance of the process in Figure 33-3-4 is greater than that in Figure 33-3-5; this is an important factor because the process with a higher capacitance will respond differently to a load change than will the process with a lower capacitance. Specifically, for a given disturbance variable, the high-capacitance process will undergo a greater change. The energy-storing ability of the low-capacitance process is greater than that of the high-capacitance one. Capacity and capacitance are important in the study of process dynamics, which is significant in the automatic control of processes.

The dynamic properties of other processes and their response to load changes are important topics in the study of control systems. The control of fluid flow is, perhaps, the most common of all processes. In the discussion of level control up to this point, the flow of material into and out of different tanks was regulated to control the level. Flow quantities, however, were not controlled. The first consideration in the control of any process is process measurement. Flow was not measured in any of the previously-mentioned processes, but was the manipulated variable. Flow

is, in fact, the manipulated variable for the control of most processes. Although not necessarily controlled to exact quantities when used as a manipulated variable, the control of flow is necessary in many applications.

## LOW-ENERGY PROCESSES

The flow control process in Figure 33-3-6 operates upon the same principles as the level processes previously discussed. The transmitter measures the flow, generates a signal proportional to flow, and transmits the signal to a controller. The controller compares the process-variable signal from the transmitter with the set point and generates a signal (which is a function of the difference between the two). The signal positions the control valve to maintain the flow at the desired value.

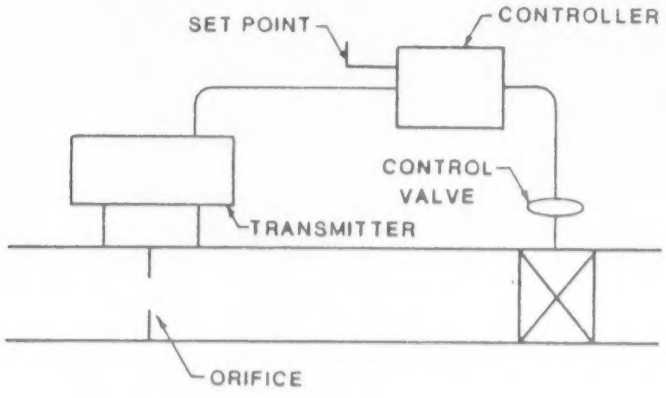


Figure 33-3-6. A flow control process.

Obviously, the amount of energy stored in the flow process is small compared to that of level processes. This low-energy characteristic of the process is a significant matter in the control of the flow loop since a slight change in valve position will cause a response in flow almost immediately.

The temperature process in Figure 33-3-7 is yet another type found in industrial facilities. Its operation is similar to that of other processes, with one major exception. Temperature processes have the inherent ability to store great amounts of energy and to exhibit large amounts of dead time. These process characteristics will be discussed with reference to the temperature process illustrated in Figure 33-3-7.

Operation of the heat exchanger illustrated in Figure 33-3-7 is straightforward: The product to be heated flows through the tubes, and hot water flows through the shell portion of the exchanger or over the outer surfaces of the tubes. Operation of this type of heat exchanger could be compared to that of the radiator on an automobile. The major difference in the two is that an automobile radiator cools the product; whereas, the process in Figure 33-3-7 heats a product.

For the sake of illustration, assume that the material flowing out is heated to the desired temperature and that the hot water is flowing in at a constant rate, controlled by the valve on the cold-water outlet line. Remember that if all conditions remain constant, the temperature of the product will be controlled at a constant value and that the control-valve position will be in at a fixed value. Again, under these circumstances, a control system is not required; however, a control system is needed when there

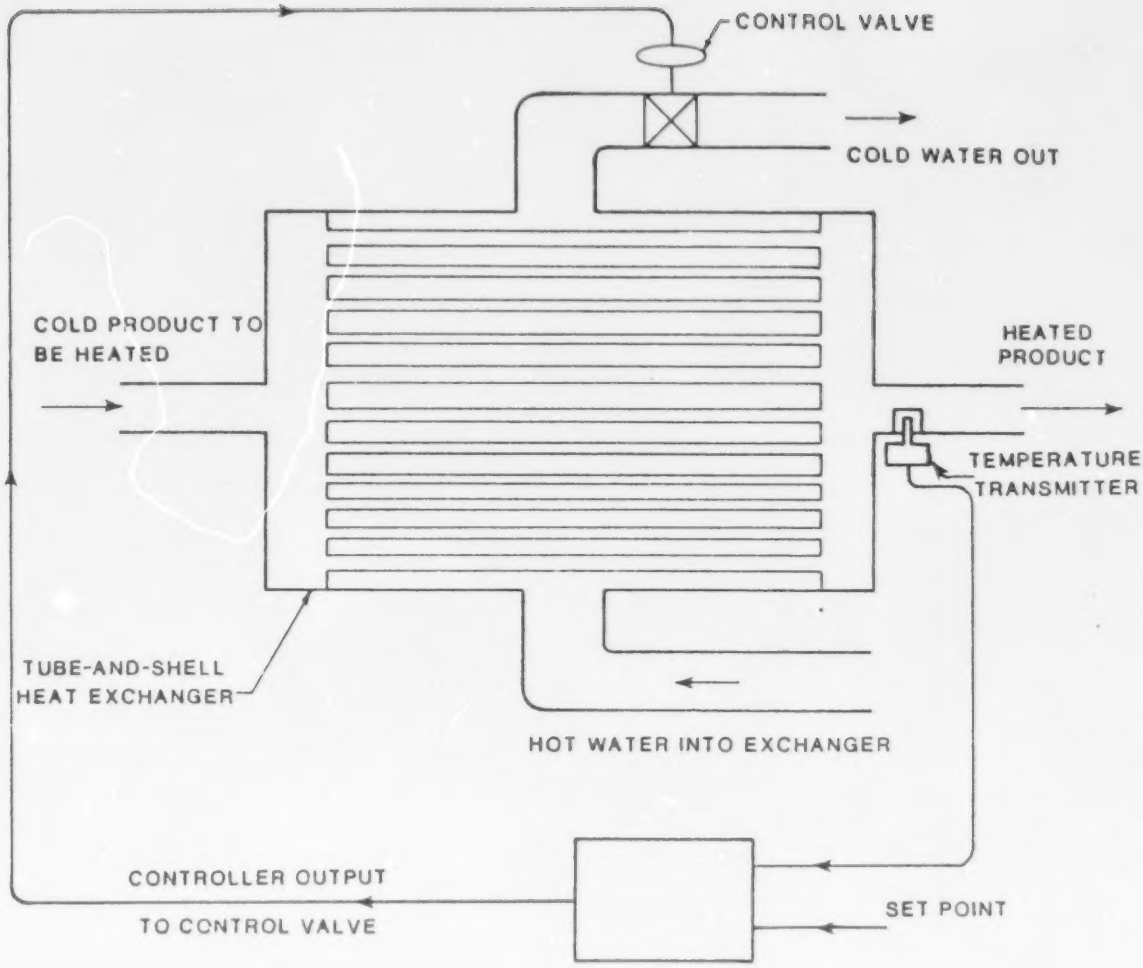


Figure 33-3-7. A temperature process that utilizes a tube-and-shell heat exchanger.

is a load change on the process. If the flow of cold product into the exchanger is increased without an increase in the flow of hot water, the temperature of the hot product out of the exchanger will decrease; therefore, a control system is needed.

When a load change does occur, causing a change in the temperature of the product, the process-variable signal to the controller will change. The change in signal will cause a deviation between the set point and the process signal, thus producing a change in controller output. This change in output signal will cause a repositioning of the control valve, changing the amount of hot water (manipulated variable) that flows into the heat exchanger. The valve position will continue to change until the heat product flowing from the exchanger is of sufficient temperature to re-establish the balance between the process-variable signal and the process set point. The purpose of any control system is to achieve this balance.

## AUTOMATIC FEEDBACK CONTROL

The level-, flow-, and temperature-control systems described in this module are classified as feedback control systems. The term "feedback" describes a control system in which a measurement of the process is fed back into the controller and causes the controller output to change. This concept is basic to the field of control-system technology, and its complete understanding is essential.

The greatest disadvantage of a feedback control system is the lack of corrective action taken by a controller until after a change in process or a deviation from set point; that is, the very medium to be controlled must change before corrective action will be taken. Despite this disadvantage most control systems are of the feedback type.

Processes to be controlled by means of a feedback system usually exhibit "self-damping," which means that the process

returns to a stable state following an upset or change in disturbance variable. When started in motion, a pendulum will decrease the distance of each successive swing until, finally, it comes to a complete rest; therefore, the pendulum is self-damping. If the pendulum is started in oscillatory motion and if no outside energy sources such as clock springs are applied, the oscillations will cease rather quickly. Processes behave in a similar way. The capacitive and resistive elements of the system tend to dampen all changes in such a manner that after disturbances, process stability eventually is restored. When processes do not behave in this fashion, independent energy sources are acting on the system and must be eliminated before automatic control can be achieved. (More will be said in later modules about such achievement of automatic control.)

## EXERCISES

1. For the process displayed in Figure 33-3-7, determine the valve operation and controller action that will provide for –
   a. High-temperature, fail-safe operation.
   b. Low-temperature, fail-safe operation.

   Fill in the following table:

| | Fail High | Fail Low |
|---|---|---|
| Valve operation | | |
| Controller operation | | |

2. Draw the schematic of a process that controls the temperature of a product by adding cooling water. This process will be similar to the one illustrated in Figure 33-3-7. Select valve operation and controller action to provide both fail-high and fail-low operation. Complete the following table:

| | Fail High | Fail Low |
|---|---|---|
| Valve operation | | |
| Controller operation | | |

## MATERIALS

Pump ($P_1$) – an electrically-operated pump that will deliver 10 to 20 gpm flow against a 20 psi head pressure.

Two control valves, diaphragm operated by 3-15 psi signal. The valves can be single-seated, signal to open, with a 1-inch body and 1/2-inch trim.

Two strip-chart recording controllers, each with fast (1 inch/min) and slow (1 inch/hr) (approximate) chart speed. The controller can be either electronic or pneumatic, although a pneumatic one is required for beginning students. Conventional controllers with 3-15 psi input and 3-15 psi output should be used.

Two tanks of approximately 20-gal volume each for use as the reservoir and process. The reservoir should be flat, about 10" in height; and the one utilized for the process should be cylindrical, about 10-12 inches in diameter.

One level transmitter (pneumatic) with adjustable range.
One flow transmitter with integral orifice and adjustable range.
Assorted hoses or pipe and tubing with which to connect the process and instruments.
The general specifications probably should be presented to an instrument company for design and construction.

## PROCEDURES

1. Set up a combination flow-and-level system as illustrated in Figure 33-3-8.
2. Identify all components in Figure 33-3-8; especially, locate the following components:
   - Flow transmitter ($T_1$).
   - Flow controller ($C_1$).
   - Flow control valve ($V_1$).
   - Level transmitter ($T_2$).
   - Level controller ($C_2$).
   - Level control valve ($V_2$).
3. Refer to the equipment instruction manuals; and by "manual" or "hand" control, position both valves to ascertain proper operation. Note the valve operation with respect to signal-to-open or signal-to-close.
4. With a water hose or other source of water supply, fill the water reservoir.
5. With the level controller in manual operation, close $V_2$.
6. Open $V_1$ half way. The half-open valve position can be determined by observing the position indicator on

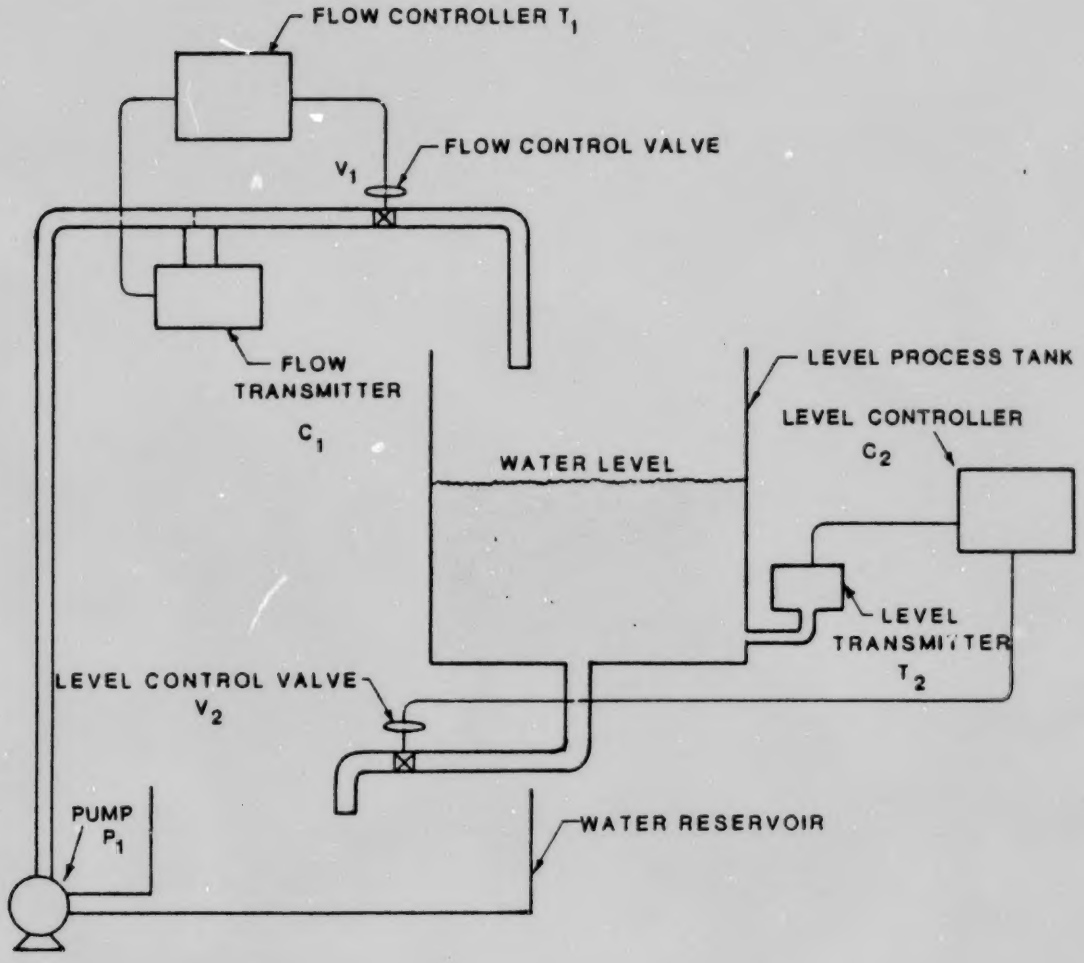


Figure 33-3-8. A combination flow-level loop.

the valve. (Refer to the instruction manual for the valve.)

7. Refer to instrument instruction manual and to Course 3, "Principles of Process Instrumentation," and perform starting procedure for the flow- and level-measuring instruments.

8. Start $P_1$ and establish the flow into the tank at a nominal value (25% to 50% as measured by the flow-measuring instruments).
9. With the flow maintained constant at the value established in Step 8, monitor level in the tank by observing the level-measuring instruments.
10. When the level reaches about 50% of its maximum value, open $V_2$ by means of the level controller on manual control; and, by repeated adjustment as necessary, find the proper valve opening of $V_2$ to maintain the level at a constant value of 50%.
11. By completion of the procedures to this point, $V_2$ has been controlled manually to maintain a balance between supply (water entering the tank) and demand (water leaving the tank) on the level process.
12. Increase the flow into the tank by 10% of the maximum value, and adjust $V_2$ to maintain the level at the original value.
13. Decrease the flow by 20% of the maximum value, and adjust $V_2$ to maintain the level at the original value.
14. By completion of Steps 12 and 13, manual control (open loop) of a process load change has been accomplished.
15. The procedures for this exercise have been completed. Secure all equipment by stopping $P_1$, closing $V_1$, and opening $V_2$ to return the water to the reservoir.

## DATA TABLE

None.

# REFERENCE MATERIALS


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Harrer, J.M. and Beckerley, J.G. Nuclear Power Reactor Instrumentation Systems Handbook, Vol. 1. Springfield, VA: U.S. Atomic Energy Commission, Office of Information, Technical Information Center, 1973.

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1. Define the following terms:
   a. Process.

   b. Disturbance variable.

   c. Manipulated variable.

   d. Negative feedback.

2. State the objective of a control system with respect to load changes and constant load.

3. Describe the operation of a feedback control system.

4. Explain the principle of the self-damping of a process.

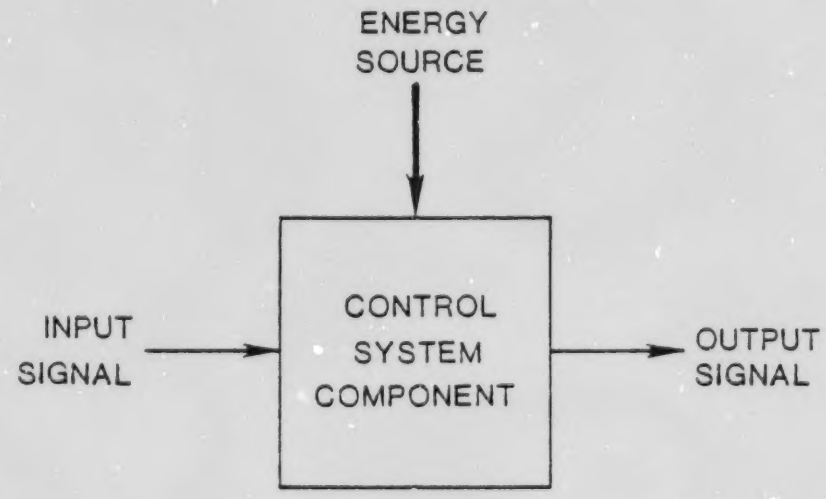
5. Explain the relationship between process damping and stability.

6. List the advantages of automatic feedback (closed-loop) control over manual (open-loop) control.

# NUCLEAR TECHNOLOGY

## MODULE 33 - 4

PNEUMATIC CONTROL MECHANISMS




CONTROL SYSTEMS I

COURSE 33

ORD CENTER FOR OCCUPATIONAL RESEARCH AND DEVELOPMENT

# COURSE MODULES

CONTENTS

COURSE 33 CONTROL SYSTEMS I


MODULE 33-1 Introduction to Block Diagrams
MODULE 33-2 Input/Output Devices
MODULE 33-3 Control System Theory
MODULE 33-4 Pneumatic Control Mechanisms
MODULE 33-5 Control Valves
MODULE 33-6 Process Control Characteristics



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## INTRODUCTION

This module introduces basic pneumatic control mechanisms and is concerned with the operating characteristics of elements that comprise the basic mechanism, and with the modes of control. The basic pneumatic control mechanism is presented. The student will study pneumatic relays and the requirements and theory of different control modes. Some basic terminology also is introduced.

## MODULE PREREQUISITES

The student should have completed Course 3, "Principles of Process Instrumentation"; Course 6, "Instrumentation and Control of Reactors and Plant Systems"; and all previous Modules of this Course.

## OBJECTIVES

Upon completion of this module, the student should be able to:

1. Discuss the operational theory of a valve-type relay and the major difference between the "bleed" and "non-bleed" types.
2. Discuss the operational theory of a Linear Aspirating Relay.

3. Characterize the following modes of control in output-input terms:

   ON-OFF action.

   Proportional action.

   Reset or integral action.

4. Given an electropneumatic controller, or a diagram of one, locate adjustments for reset, rate response and/or proportional band, nozzle-flapper assembly, and pneumatic relay.

# SUBJECT MATTER

## TERMINOLOGY

The following terms must be mastered:

- A controller is a device that operates automatically to regulate a controlled variable.
- A directly controlled variable in a control loop is the variable whose value is sensed to originate a feedback signal.
- A manipulated variable is a quantity or condition that is varied as a function of the actuating error signal in such a manner as to change the value of the directly controlled variable.
- A measured variable is a quantity, property, or condition that is measured, and that sometimes is referred to as the "measurand." Common measured variables are temperature, pressure, rate of flow, thickness, speed, etc.

  A hot-water system in which steam heats the water is an example of a system having a manipulated and a controlled variable. The manipulated variable is the quantity of steam regulated to control water temperature. Frequently, the variable being measured – in this case, temperature – is referred to as the "measured variable." The student should exercise caution when using different terms to describe the same function because each term may have a definite and precise meaning according to industry standards.
- A signal is a physical variable, one or more parameters of which carry information about another variable (which the signal represents).

Controllers have at least an input signal and an output signal. Normally, the input signal represents the measured variable, and output signal is proportional or in some other way related to the input signal.

- Range is the region between the limits within which a quantity is measured, received, or transmitted. Range is expressed by the lower and upper range values. Unless otherwise modified, input range is implied.
- Span is the algebraic difference between the upper and lower range values. A controller may have a range of 0°C to 300°C. The span for this controller would be 300°C.

## BASIC PNEUMATIC CONTROLLER

Basic pneumatic controllers, which consist of a nozzle-flapper assembly, are a type of transducer and provide amplification. The nozzle-flapper assembly acts to convert a small movement (mechanical motion) into an equivalent pneumatic output signal that then can be transmitted to the control system final element or to some other element of the controller. A basic nozzle-flapper assembly is illustrated in Figure 33-4-1. Normally, 20 pounds-per-square inch (psig) of air pressure is supplied to the unit through a restriction. Normal output air pressure, referred to as "output signal," may range between 3 and 15 psig and is determined by distance between the nozzle and flapper (nozzle-flapper displacement). The restriction opening is smaller than the nozzle opening,

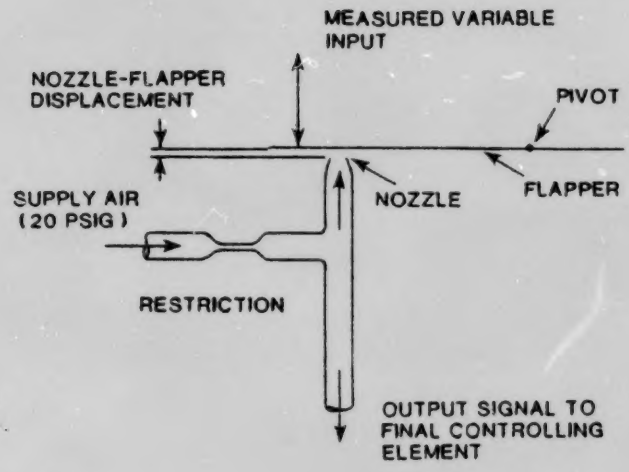


Figure 33-4-1. Nozzle-flapper unit.

which allows the output signal pressure to decrease as air flow through the nozzle increases when the nozzle-flapper displacement is increased. Conversely, decrease in the nozzle-flapper displacement causes the output signal to increase. Because a small flapper movement that measures only thousandths of an inch causes a large output signal change, this basic controller is referred to as a "pneumatic amplifer." The graph in Figure 33-4-2 indicates signal pressure that corresponds to nozzle-flapper displacement.

Flapper movement of only about 0.004" produces a proportional pneumatic signal that may vary from near zero pressure to supply pressure. The slope of the curve at any point is called "nozzle sensitivity," normally referred to as "gain." In a basic system such as this, gain is a function of both the restriction and the nozzle openings.

In some pneumatic control systems, the signal air operates the final control element. For those systems, the basic controller is less expensive, extremely reliable, and provides high gain. However, the basic pneumatic controller has the following limitations: (1) When the output signal air operates

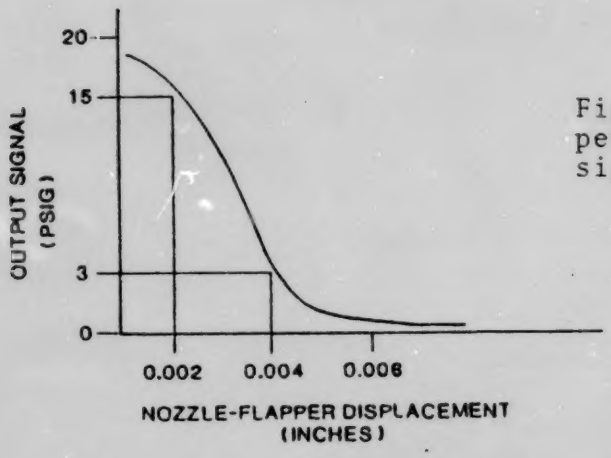


Figure 33-4-2. Nozzle-flapper displacement and output signal relationship.

a valve or other similar element, the restriction produces a time lag caused by the volume of air used and by the tubing lengths. (2) Because of the small flapper displacement required to vary nozzle pressure over its full range, the system essentially functions in the "on-off" mode and is sensitive to vibration and instability.

Time lag due to the restriction may be overcome by addition of a relay that acts as a power amplifier. In this case, the nozzle-flapper mechanism functions as a signal amplifier; and the "on-off" action may be removed by an added feedback mechanism that repositions the flapper or nozzle.

## PNEUMATIC CONTROL RELAYS

Pneumatic relays are employed along with a nozzle-flapper unit, as in Figure 33-4-3, to increase gain and, as is the case in many pneumatic control systems, to increase airflow capacity. Relays may be direct acting (the output signal increases as the nozzle pressure increases) or reverse acting

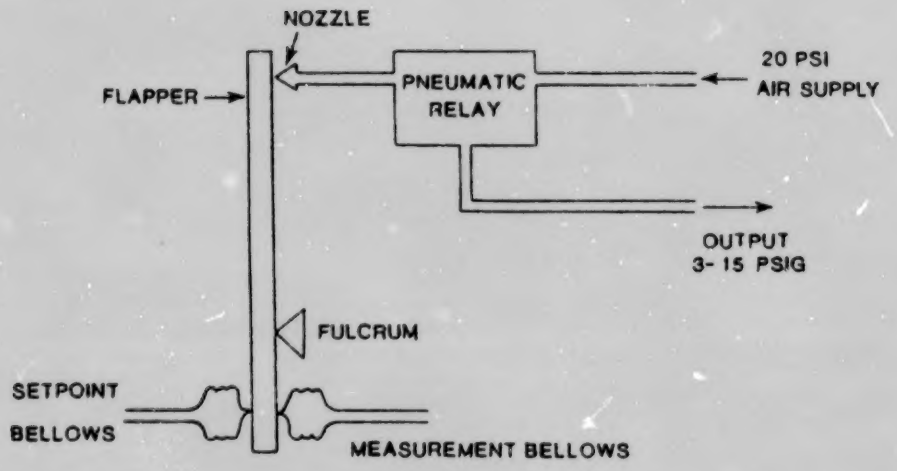


Figure 33-4-3. On-off pneumatic controller.

(the output signal decreases as the nozzle pressure increases). Relays also may be biased in order that there is no output response until nozzle pressure reaches a maximum value or falls to a minimum value. Bias enables the nozzle-flapper unit to function over the linear portion of its characteristic curve.

## VALVE-TYPE RELAY

A valve-type relay contains a small valve connected to, and operated by, a diaphragm. The diaphragm causes the valve stem to move, either opening or closing the valve. The diaphragm has a large surface area; therefore, small pressure changes acting on its surface result in large force changes required to move the valve stem.

Supply air enters the relay from two directions. First, it flows through a restrictor and then is diverted to the nozzle and also into a chamber in the relay, where it can act on

the diaphragm. Then supply air enters the realy without restriction and, depending on relay action, may be diverted to the output signal port and/or to the exhaust air port.

A single diaphragm-valve relay is illustrated in Figure 33-4-4. In this relay, a decrease in nozzle-flapper displacement causes an increase in air pressure acting on the relay

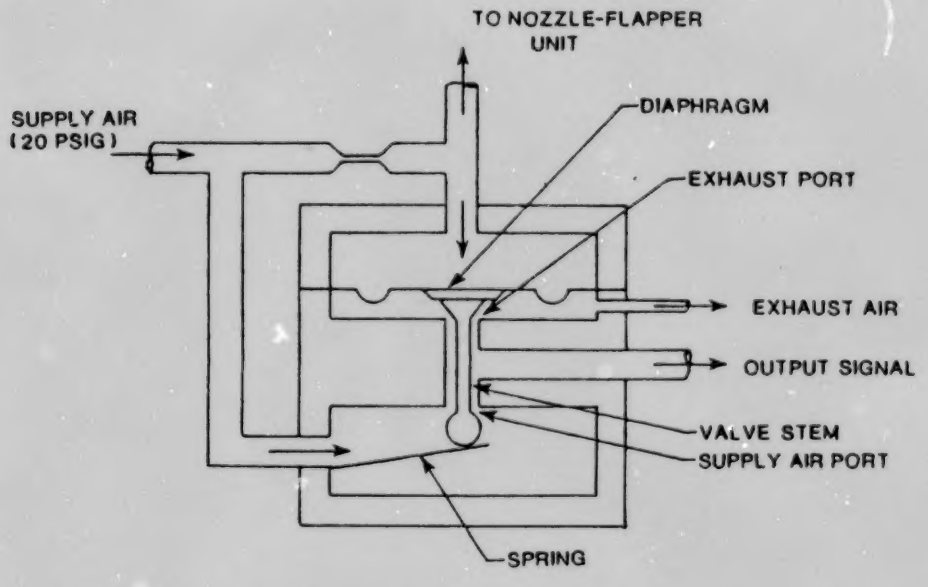


Figure 33-4-4. Direct-acting pneumatic relay (bleed type).

diaphragm. The diaphragm is moved, causing the ball valve to open and allowing supply air to pass through the relay. Air exits the relay through the output signal port and/or the exhaust air port. Increase in nozzle-flapper displacement causes operation of the relay to be reversed. When nozzle pressure is maximum, the exhaust-air valve is closed, and maximum output signal pressure and flow are provided to the final element actuator. When nozzle pressure is at the

minimum value, the supply-air valve is closed; and air in the transmission line between the relay and actuator is exhausted to the atmosphere. At any output signal between minimum and maximum, the supply-air and exhaust-air valves are open; and 1/16" vent air is used. Consequently, the single-diaphragm, valve-type relay is termed a "bleed-type" relay. The spring that acts upon the valve stem provides relay bias.

A "nonbleed-type" relay is depicted in Figure 33-4-5. This valve is used widely in pneumatic controllers because it produces less drain on the supply air system. A force-

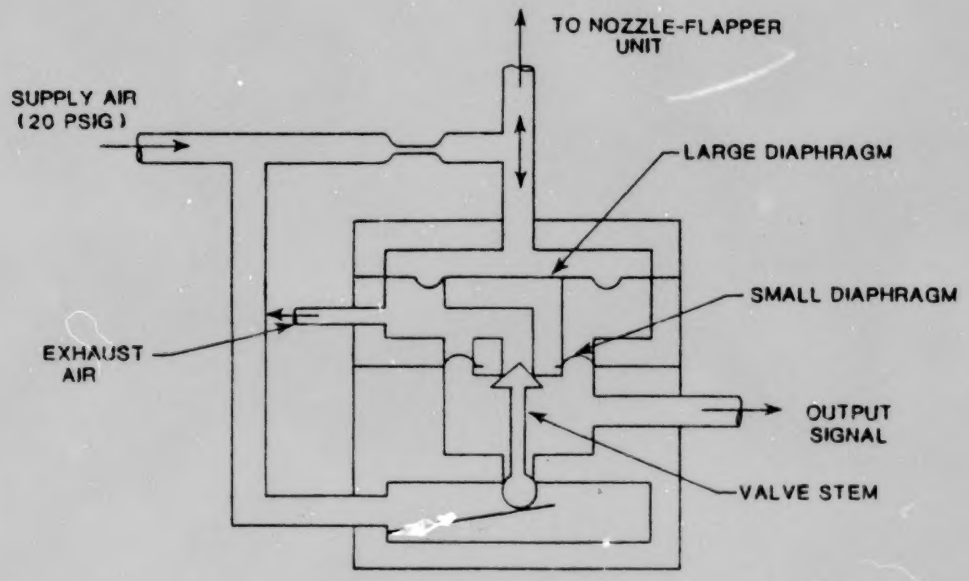


Figure 33-4-5. Pneumatic relay (nonbleed-type).

balance and feedback principle is achieved by its two diaphragms. The diaphragm subjected to nozzle pressure is larger than the diaphragm subjected to output signal pressure. At steady state, both the supply-air and exhaust-air valves are closed. As nozzle pressure increases, both diaphragms

are forced downward, causing the air-supply valve to open and admitting supply air. Supply air increases output signal pressure until the diaphragms are moved upward, causing the supply-air valve to close and achieving the previously balanced condition that existed when both valves were closed. Similarly, a reduction in nozzle pressure causes the diaphragms to raise, opening the exhaust valve and reducing the output signal pressure.

## LINEAR ASPIRATING RELAY

When flow or volume requirements are small, a linear aspirating relay may be employed; this unit frequently is referred to as the "aspirating relay." This relay employs the venturi-tube principle and actually resembles a small venturi (Figure 33-4-6).

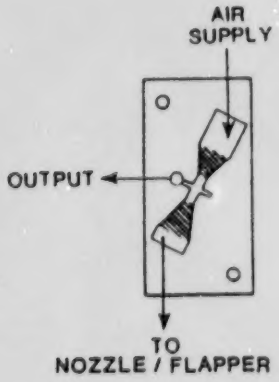


Figure 33-4-6. Linear aspirating relay.

Supply air enters one end of the venturi, and nozzle air leaves from the opposite end. Output-signal air is

supplied from the throat of the venturi. Output signal pressure can vary 3-15 psi, with a nozzle-flapper displacement of less than 0.001". As nozzle-flapper displacement decreases, flow of air through the venturi decreases; and pressure at the throat of the venturi increases, causing an increase in output signal pressure. Conversely, as nozzle-flapper displacement increases, flow through the venturi increases; and pressure at the throat decreases, causing the output pressure to decrease.

The aspirating relay provides pneumatic amplification with almost perfect linearity, and its parts usually are not subject to wear. This type of relay offers many advantages when a high-volume output is not required.

## MODES OF CONTROL

The purpose of a process control system is to maintain the process variable (the controlled variable) within desired limits or at a specific set point. This frequently is achieved by manipulation of an input-output signal related to the controlled variable. A controller measures the controlled variable and operates to limit how much the variable deviates from a set point. Pneumatic controllers offer a number of modes for control of the controlled variable. These modes are named to describe response of the final element to changes of the controlled variable below or above the set point. Four common modes of control are (1) on-off action, (2) proportional action, (3) reset or integral action, and (4) derivative, or rate-of-response, action.

ON-OFF ACTION

On-off action is cyclic, and the final element may function as either fully open or fully closed. The controlled variable fluctuates about the set point between maximum and minimum values. The controller has no feedback other than the process itself, and, typically, the nozzle-flapper assembly is a high-gain unit. Also, the relay may have a gain of three or more. In this type of controller, a small change in input signal will result in a large change in output signal. A system of this type is displayed in Figure 33-4-3, and a typical response curve is provided in Figure 33-4-7.

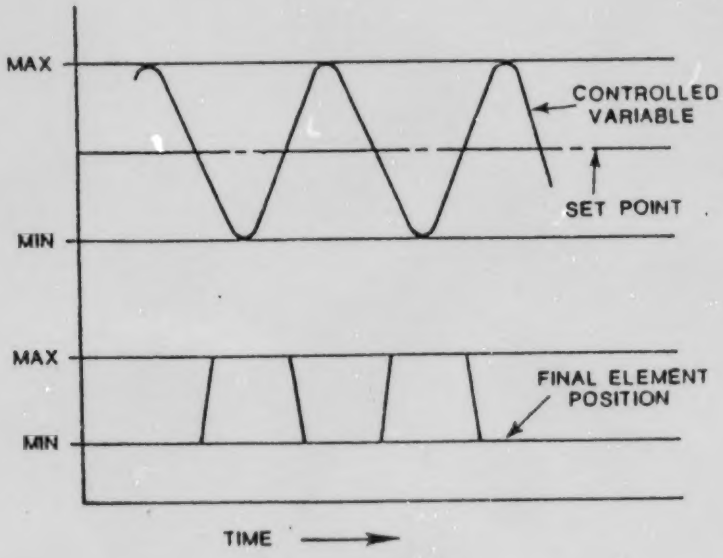


Figure 33-4-7. On-off action response curve.

When the controlled variable moves above or below the set point, the flapper is caused to move away from, or closer to, the nozzle, resulting in a decrease or an increase in

output-signal air pressure and flow to the final element. Because the nozzle-flapper assembly is a high-gain unit, a very small change in nozzle-flapper displacement results in a maximum or minimum positioning of the final element.

On-off mode of control is ideal for a batch process such as a heating system, when the controlled variable change is relatively small and slow or when input-to-output energy balance is unimportant. A disadvantage of this system is that the controlled variable is allowed to vary continuously over a range of values. The range can be decreased; however, if the range is too narrow, the system will "hunt" and will be unstable.

## PROPORTIONAL ACTION

Many processes require that the value of the controlled variable remains constant. In the on-off mode of control, the final element normally is functioning at either maximum or minimum capacity, and the controlled variable continually swings between a maximum or a minimum value that ranges about the set point. This erratic operation is not always acceptable, for instance, it is unacceptable on a fast system that requires quick action to maintain a constant value for the controlled variable. Proportional action allows the final element to establish a position relative to the value of the controlled variable, and any deviation of the value of the controlled variable from the set point will cause a proportional change in the position of the final element.

The primary purpose of a proportional controller is to stabilize the controlled variable. This function is

accomplished with one limitation: The controlled variable does not stabilize at the set point, except at one specific process load. The point at which the controlled variable stabilizes is referred to as the "control point"; the difference between the control point and the set point is called "offset." "Proportional control" is so named because the final element is repositioned at some percent of full stroke proportional to the change in the controlled variable. Proportional control is achieved by use of an internal proportional bellows that has a negative feedback function and that tends to reposition the flapper or nozzle after response to a change of the controlled variable. Figure 33-4-8 illustrates a basic proportional controller.

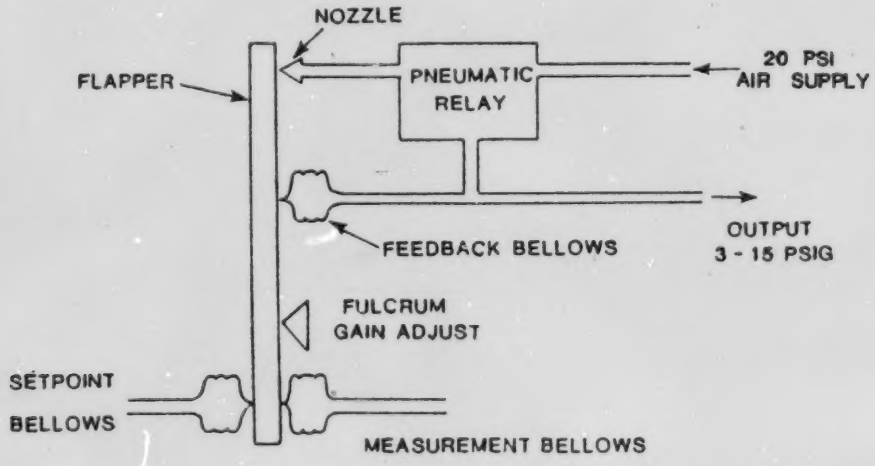


Figure 33-4-8. Proportional Controller.

The amount of change that the final element undergoes for a given change of the controlled variable is determined by the controller and its proportional band. Proportional band is expressed as a precentage of the sensing element

range; that is, for a proportional bank of 100 percent, a controlled variable change equal to the span of the sensing element would cause the controller output signal to change from one limit to the other limit. Similarly, for a proportional band of 50 percent, a controlled-variable change equal to one-half the span of the sensing element would cause the output signal to change from one limit to the other limit. In many controllers, the proportional-band adjustment also is referred to as "proportional gain." Proportional gain is a ratio and may be defined as the percent of valve stroke divided by percent of the sensing element range. For example, if a 20 percent change in the sensing element causes a 100 percent change in valve stroke, the proportional gain is 5. Thus, the controller effectively proportions the controller output over only 20 percent of the sensing element range, and the proportional band is 20 percent. Both proportional band and proportional gain commonly are used.

In the proportional controller illustrated in Figure 33-4-8, the flapper bar pivot point can be changed to adjust the proportional band. The band is narrowed when the pivot point is moved closer to the nozzle; it is widened when the pivot point is move away. Offset will not exceed one-half the proportional band. The greater the proportional band, the greater the offset that may exist. A proportional-band curve is given in Figure 33-4-9. Curve "A" illustrates a proportional band of 100 percent, and curve "B" illustrates a band of 50 percent. Figure 33-4-10 illustrates a typical proportional-action response curve.

For the basic proportional controller represented in Figure 33-4-8, an increase in the controlled variable value causes the flapper to move toward the nozzle and increases loading on the relay, which causes an increase in output

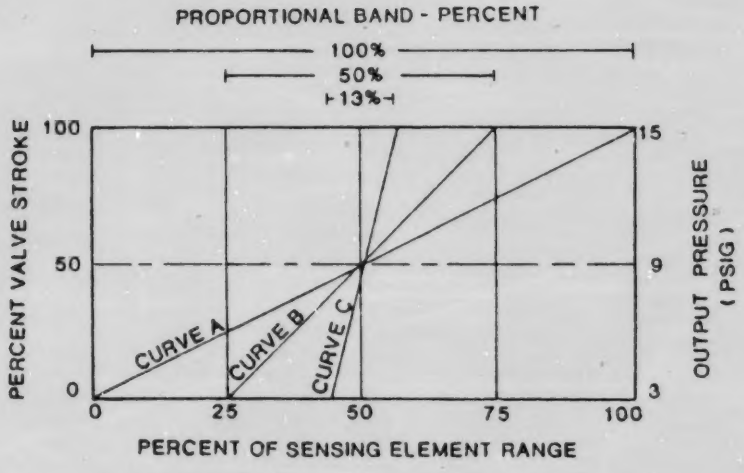


Figure 33-4-9. Proportional band curves.

signal and a corresponding change in position of the final element. The output signal also is transmitted to the feedback bellows (proportional element), counteracting flapper movement and equalizing relay diaphragm pressure to cause the final element to remain at a new position, which is proportional to the change of the controlled variable. Thus, the controlled variable settles out at a new value and remains there until another system load change, or other change, occurs.

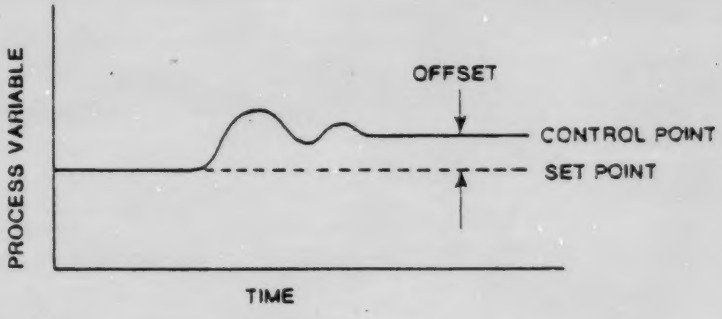


Figure 33-4-10. Typical proportional-action response curve.

RESET, OR INTERGRAL, ACTION

Except for offset, proportional control would be acceptable for most systems. Many processes require that the measured variable remain at a constant value equal to the set point. To achieve this function, a reset action is added to the controller to cause the control point to return to the set point. In other words, integral action automatically will eliminate the offset. Output of a proportional controller is based upon error deviation from set point; output of the integral controller is based upon the integral of the error.. Reset, or integral, action may be utilized alone to provide controlling action; however, response speed is fairly slow. Consequently, this action normally is added to a proportional controller, and the resulting controller is called a "proportional-integral controller." Reset action is attained by addition of a reset bellows that also functions off of the output air, but opposes the proportional bellows. Figure 33-4-11 illustrates a basic proportional-integral controller.

Increased output air pressure causes pressure in the reset bellows to increase, and this, in turn, causes the flapper to move closer to the nozzle (Figure 33-4-11). This action causes another pressure increase throughout the system, and pressure buildup continues until the controlled variable returns to the set point. A variable restrictor normally is placed in the air line to the reset bellows. The restrictor can be ajdusted to vary the effect of reset action.

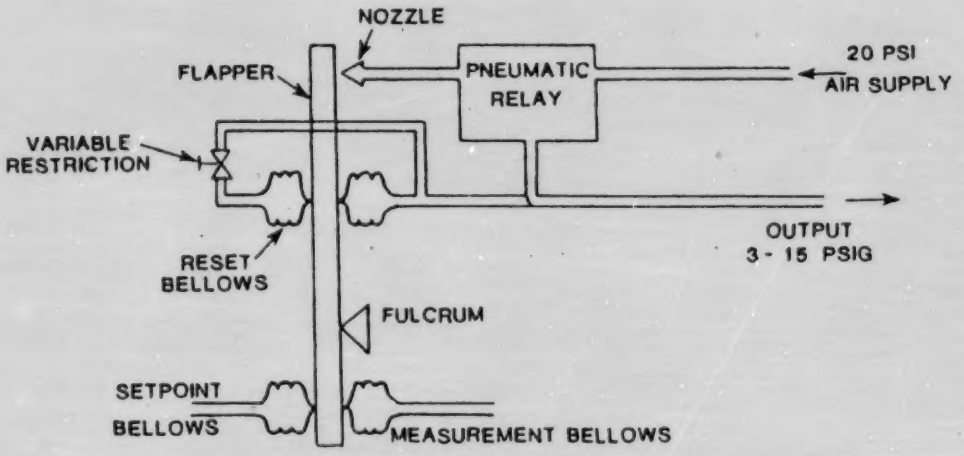


Figure 33-4-11. Proportional-plus-integral controller.

DERIVATIVE, OR RATE, ACTION

Another control action available for process control is the derivative mode. However, unlike integral action, derivative action cannot be used alone. Normally, this mode is coupled with proportional action, and the resulting controller is termed a "proportional-derivative controller." Output of a proportional-derivative controller is based upon the rate at which the change of the deviation of the controlled variable occurs. It is suitable for processes that have inherent time delays between the time at which a change occurs in the process and the time at which the measured variable change is supplied to the control mechanism. A heating system is such a process. Derivative action, in a sense, is an anticipating action that responds to the rate of change of the error. When change is fast, the controller responds by making a large corrective change. The reverse is also true. Derivative action is added to a proportional controller by

installation of a variable restrictor in the air line going to the feedback bellows (Figure 33-1-12). This restriction causes corrective action of the feedback bellows to be delayed. Amount of delay varies with rate at which the deviation between the control point and set point is changing. This type of controller, like the proportional controller, is designed to stabilize the measured variable and is subject to offset in the same way.

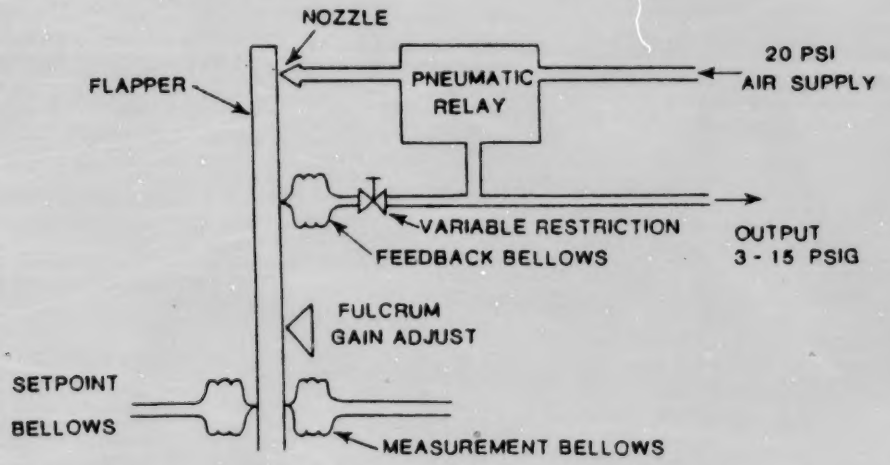


Figure 33-4-12. Proportional-plus-derivative controller.

## THREE-MODE CONTROLLER

The better stability feature of the proportional-derivative mode and the no-offset feature of the proportional-integral mode are combined into a single controller called the "proportional-derivative-integral controller." A basic controller of this type is diagramed in Figure 33-4-13. These controllers usually are designed to handle any process.

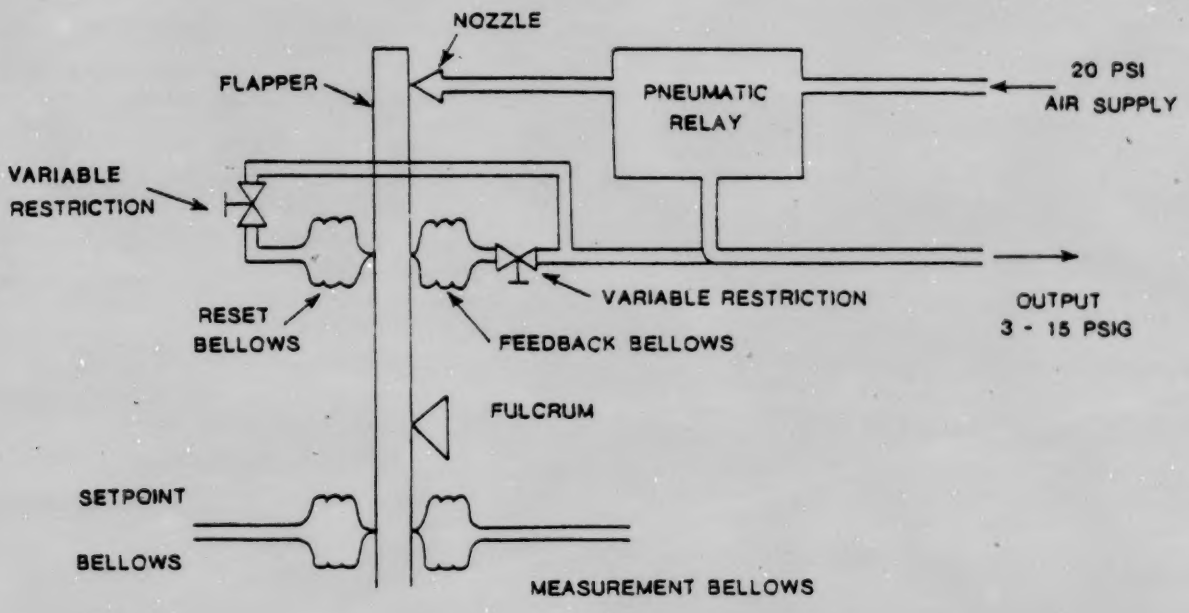


Figure 33-4-13. Three-mode (proportional + integral + derivative) controller.

Adjustments for each of the actions are independent, and changes in the response of one action normally requires adjustment of the other actions.

## ELECTROPNEUMATIC CONTROL

Control systems may incorporate both electric and pneumatic control. One such unit, an electropneumatic converter (Figure 33-4-14), is employed when pneumatic control of the final control element is required and when the input signal from the measured variable is electric. The unit will convert the electric signal to a proportional pneumatic signal by a movable electric coil positioned in a permanent magnet. A direct-current electric input signal from the measured

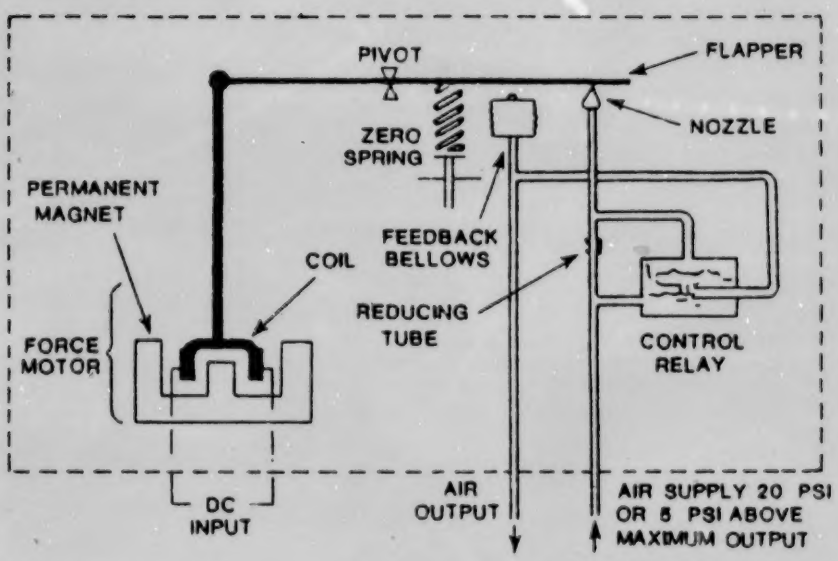


Figure 33-4-14. An electro-pneumatic converter.

variable is applied to the movable coil, and an axial thrust proportional to the d.c. signal results. This thrust causes the flapper to move, changing the nozzle-flapper displacement and causing a change in the relay output. The pneumatic portion functions as previously described for pneumatic controllers.

## EXERCISES

None.

## MATERIALS

Instrumentation control process trainer.

## PROCEDURES

On a three-mode pneumatic process controller, perform the following functions:

1. Adjust reset and rate actions to the least effective settings; adjust gain to a low setting.
   a. Determine ultimate gain; increase gain until the process just begins to oscillate.
   b. Adjust gain to obtain quarter amplitude-decay response.
   c. Observe offset.
   d. Increase offset.
   e. Decrease offset.
2. Adjust gain to a low setting; add reset action.
   a. Observe results.
   b. Increase gain; observe results.
   c. Increase reset action; observe results.
3. Adjust gain to a low setting and reset action to the least effective setting; add rate action.
   a. Observe results.
   b. Increase gain; observe results.
   c. Increase rate action; observe results.

4. Adjust gain to obtain quarter amplitude-decay response, add reset action and rate action while maintaining quarter amplitude-decay response.
   a. Observe results.
   b. Vary reset and rate actions; observe results.

# DATA TABLES

None.

# REFERENCE MATERIALS


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Bateson, Robert. Introduction to Control Systems Technology. Columbus, OH: Charles E. Merrill Publishing Company, 1973.

Considine, Douglas M. Process Instruments and Controls Handbook. 2nd ed. New York: McGraw-Hill Book Company, 1974.

Kirk, Franklyn W. and Nicholas, Rimboi R. Instrumentation. 3rd ed. Chicago: American Technical Society, 1975.

Yothers, Mark T., ed. Standards and Practices for Instrumentation. 5th ed. Pittsburgh: Instrument Society of America.

1. Sketch a schematic of the following pneumatic controllers:
   a. On-off action.

   b. Proportional action.

c. Proportional plus integral action.

d. Proportional plus derivative action.

e. Proportional plus derivative plus integral action.

2. Explain the theory of operation of a valve-type non-bleed relay.

3. Explain the theory of operation of a linear aspirating relay.

4. Characterize the following modes of control in output-input terms.
   a. On-off action.

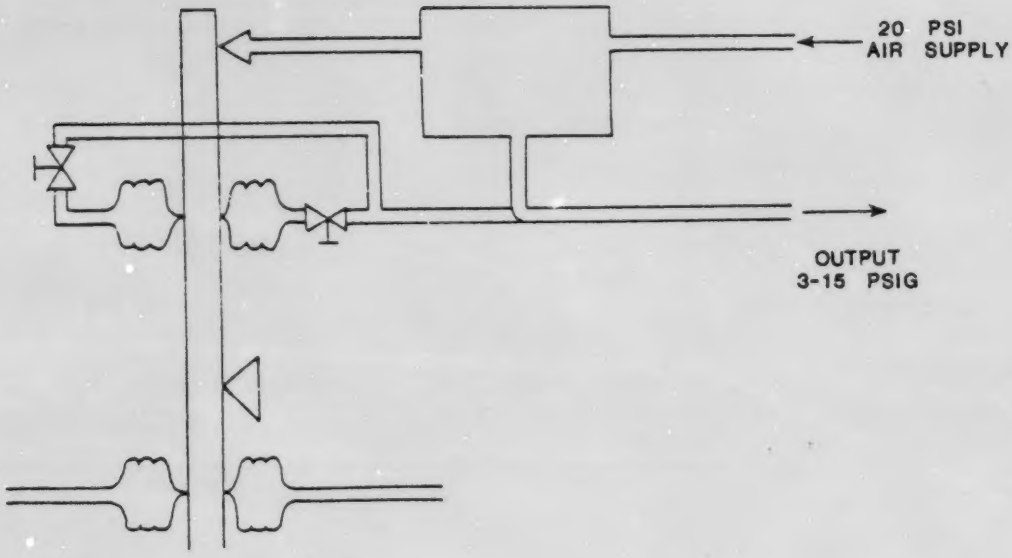
   b. Proportional action.

c. Proportional plus integral action.

d. Reset or integral action.

e. Derivative or rate action.

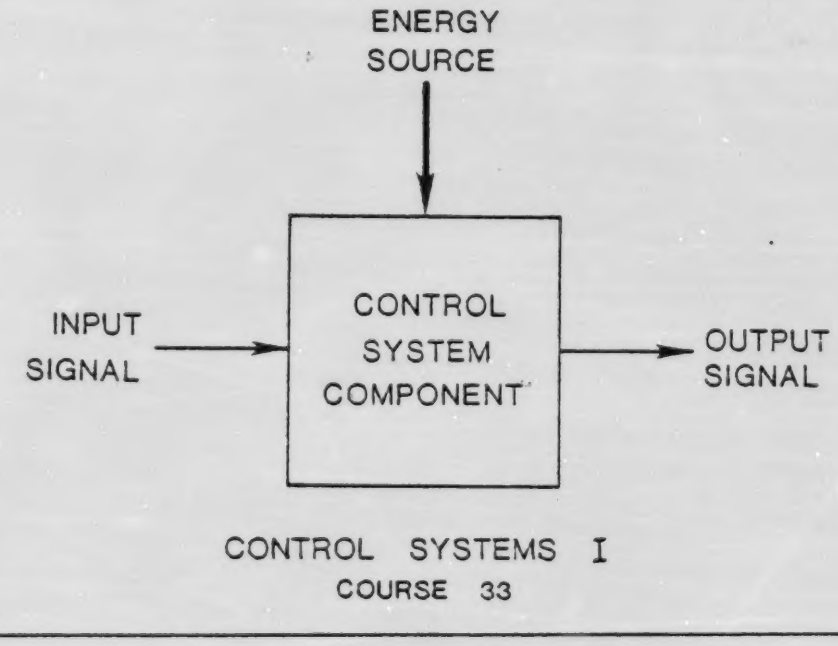
5. Given the accompanying schematic of a three-mode (proportional plus-integral-plus-derivative) pneumatic controller, properly identify the following elements:
   a. Nozzle-flapper.
   b. Control relay.
   c. Set-point adjustment.
   d. Proportional element.
   e. Integral element.
   f. Derivative restrictor (adjustment).
   g. Proportional band (gain) adjustment.
   h. Integral restrictor (adjustment).


20 PSI
AIR SUPPLY
OUTPUT
3-15 PSIG

# NUCLEAR TECHNOLOGY

## MODULE 33-5

CONTROL VALVES




CONTROL SYSTEMS I
COURSE 33

ORD CENTER FOR OCCUPATIONAL RESEARCH AND DEVELOPMENT

CONTENTS

COURSE 33 CONTROL SYSTEMS I


MODULE 33-1 Introduction to Block Diagrams
MODULE 33-2 Input/Output Devices
MODULE 33-3 Control System Theory
MODULE 33-4 Pneumatic Control Mechanisms
MODULE 33-5 Control Valves
MODULE 33-6 Process Control Characteristics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## INTRODUCTION

The control valve, as the final element in a process-control system, translates the messages from the process controller into action and, therefore, is a very important and essential part of the plant. A control valve must be of the correct design and correct size for a particular installation, and it must be properly installed and maintained in order to function properly. No matter how perfect the rest of a process-control may be, the entire system fails if the control valve does not operate well. The importance of the control valve cannot be stressed too strongly, for lack of appreciation of its function and operation has resulted in the downfall of many otherwise good control systems.

This module introduces the major types of control valves and discusses their characteristics, selection, and sizing.

## MODULE PREREQUISITES

The student should have completed Course 3, "Principles of Process Instrumentation," and the previous modules of this Course.

## OBJECTIVES

Upon completion of this module, the student should be able to:

1. Define the following terms:

   Globe control valves.

Butterfly control valves.
Ball control valves.
Linear characteristic.
Quick-opening characteristic.
Equal-percentage characteristic.
Parabolic characteristic.
Valve-flow coefficient.
Valve actuator.
Valve positioner.

2. Describe the operation of direct- and reverse-operating pneumatic valve actuators.
3. Draw the following typical characteristic curves of a control valve:
   Quick opening.
   Linear.
   Modified parabolic.
   Equal percentage.
4. Given the maximum flow rate, specific gravity of the fluid, pressure drop at maximum flow, safety factor and valve-flow coefficient, find the proper valve size.

## THE BASIC FUNCTION OF CONTROL VALVES

The control valve is a variable orifice whose area can be altered accurately by the output signal from a controller. Variation of the orifice in this manner controls the flow of process-control agent in the line. All control problems can be solved if the flow rate can be regulated properly.

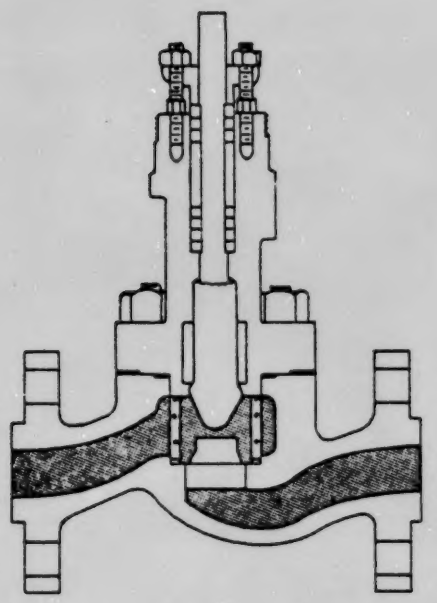
## TYPES OF CONTROL VALVES

Basically, there are three types of throttling-control valves – globe valves, ball valves, and butterfly valves.

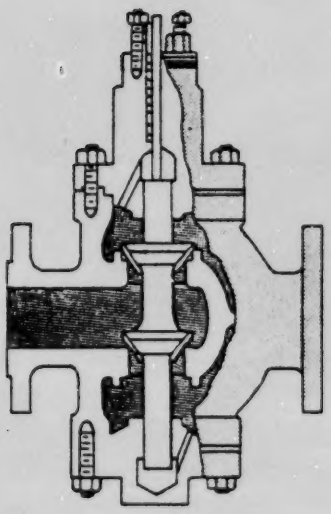
### GLOBE CONTROL VALVES

Globe valves are the most common type and are characterized by a sliding stem and contoured-plug, or the modern cage-type inner element. Globe valves with contoured plugs may be single or double ported, as illustrated in Figure 33-5-1.

The cage-type globe control valve is known for its quick-change trim feature which consists of the valve cage, plug, and seat ring. Figure 33-5-2 illustrates a typical globe control valve with cage-type inner element. Figure 33-5-3 depicts some interchangeable cages. The cage-type valve can be used for most applications because of the wide range of trim styles. This valve provides for more stable operation than the contoured-plug, mainly because the cage allows more guiding stability in the area in which maximum pressure drop occurs.



(a) SINGLE-PORTED



(b) DOUBLE-PORTED

Figure 33-5-1. Typical globe control valves.

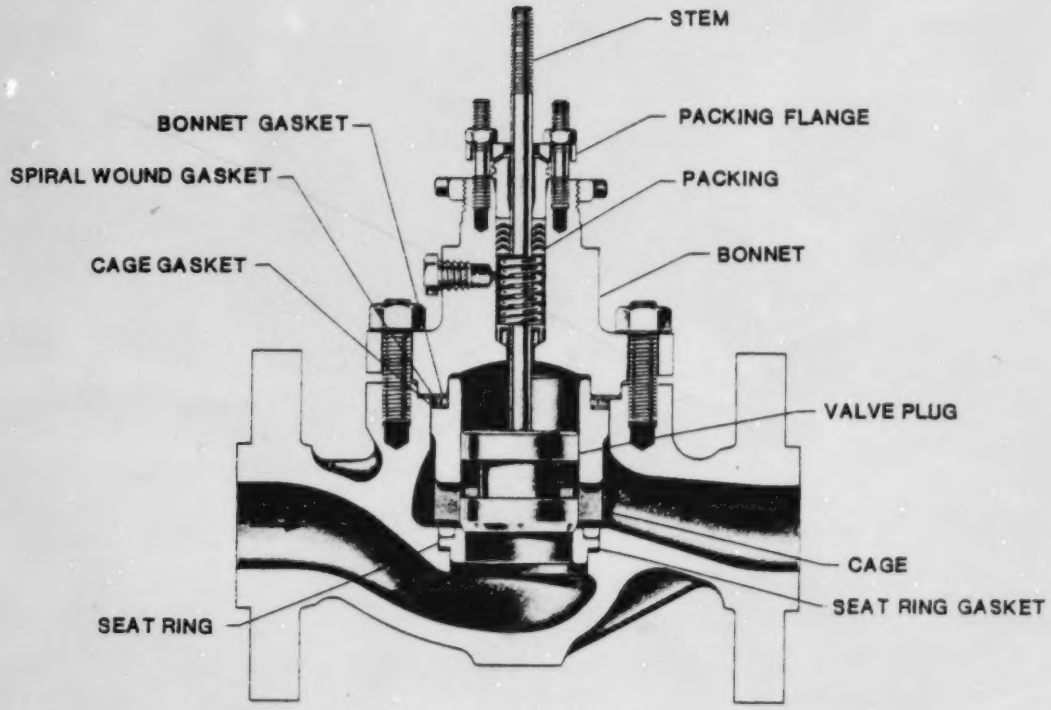



Figure 33-5-2. Globe control valve with cage inner element.

Typically, globe control valves are available in sizes up to 16" and in most castable alloys. This type of control valve is available, therefore, for systems that handle corrosive fluids, as well as those that possess high pressures and temperatures. Valve ends are of the screw, flange, or weld types.

Although the globe control valve is quite popular, it does have some disadvantages:

- The overall expense may be greater than for other suitable types.

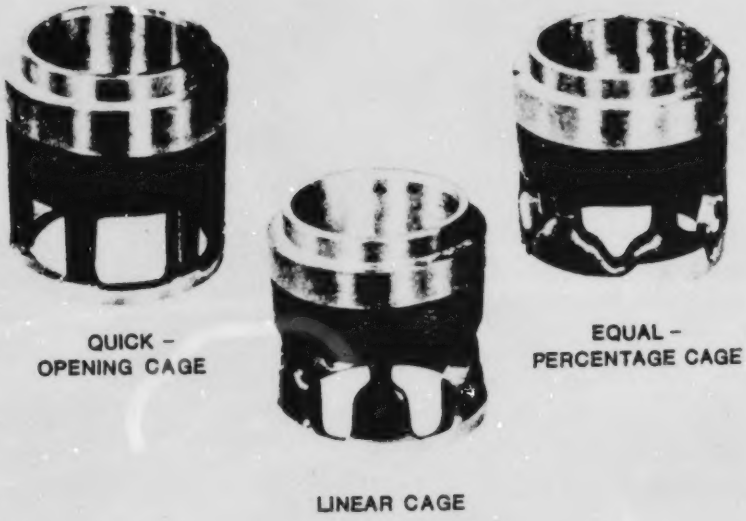



Figure 33-5-3. Interchangeable cages for a globe control valve with cage inner element.

- It has size limitations due to excessive weight.
- It has lower capacity when compared to ball and butterfly valves of equal size.
- It is less capable of handling abrasive fluids without severe erosion.

For many applications, ball and butterfly control valves may be more suitable because of lighter weight, increased capacity, and less cost. Unlike the globe type, the ball and butterfly control valves are classified as rotary-shift types because the shafts must be rotated to open or to close the valves.

BUTTERFLY CONTROL VALVES

Based on a cost-per-flow capacity, the standard butterfly valve is the most economical of the three basic types. It provides compactness and economy with high capacity and is recommended for general service not requiring low leakage rates. Flow through the butterfly valve is controlled by a disc attached to a rotary shaft, and the valve can be changed from full-closed to full-open through one-quarter turn of the shaft (Figure 33-5-4). Sealing has been a problem with these valves; however, valve bodies can be equipped with an elastomer liner to provide tight shutoff. The liner may be either replaceable or vulcanized directly to the valve body, and in many cases it provides total isolation of the body from the process fluid. Consequently, butterfly valves

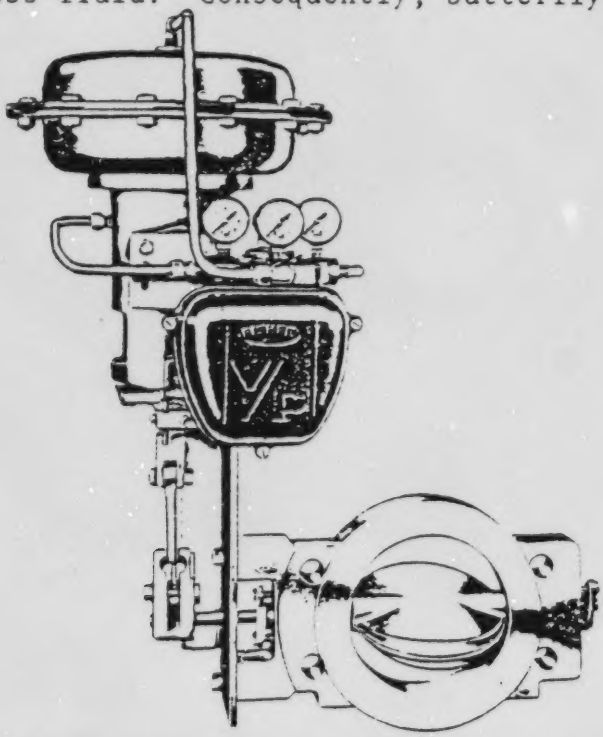


Figure 33-5-4. Butterfly control valve.

equipped with such liners have application in systems that handle corrosive fluids. On the other hand, the elastomeric component limits the temperature of the fluid to about 400°F, depending upon the type. Unlined valves can be employed in systems in which the fluid temperature ranges to 1500°F.

Butterfly valve types and sizes are designed for a wide range of pressure drops, inlet pressures, and shutoff requirements. Sizes range from as small as 1" to as large as 100". The most common sizes are 4" through 12", and a large number are up to 48". Pressure classes may range from 300 psi for lined valves to 600 psi for unlined high-performance valves.

## BALL CONTROL VALVES

The third basic type of control valve is the ball valve (Figure 33-5-5). This valve is classified into two main types: (1) the conventional full ball (which may have either a full or closed bore) and (2) the characterized segment. The characterized-segment ball valve may have a V-notch or a parabolic edge for the spherical segment of the ball. As with the butterfly valve, the ball valve may be changed from full-closed to full-open through one-quarter turn of the shaft. The majority of ball valves are equipped with elastomeric or fluoroplastic ball seals to provide tight shutoff and are limited in use to systems in which the fluid temperature will not exceed 400°F.

Compared to globe valves, ball valves require less pressure drop to produce a given flow rate, but are more limited in allowable pressure drop and temperature. Ball valves have a greater capacity to handle abrasive fluids without experiencing excessive erosion.

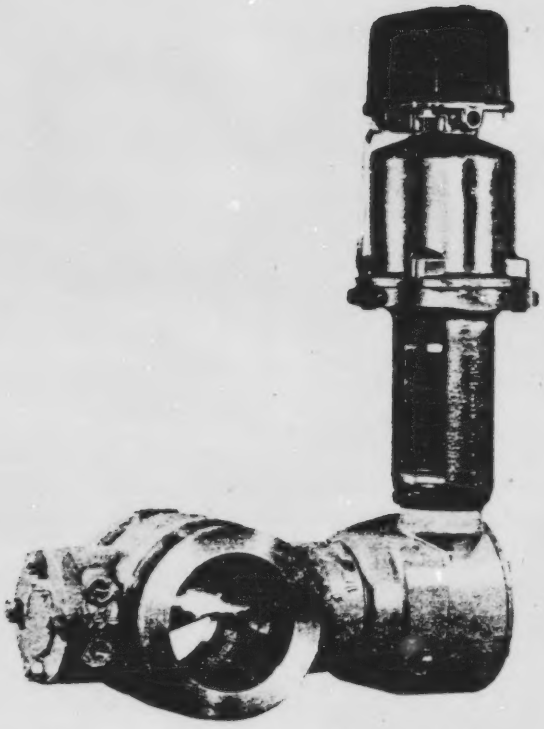


Figure 33-5-5. Ball control valve (Fisher U Vee-Ball®).

## CONTROL-VALVE CHARACTERISTICS

The characteristic of a control valve is the relationship of how the flow rate through the valve varies with stem travel. Additionally, characteristics are considered as inherent or installed. Inherent characteristics are obtained throughout the valve stroke, as under laboratory conditions. This is an ideal situation and is applied to all control valves. Thus, most characteristic curves supplied with the valve are inherent characteristics. However, in actual operation, the pressure drop normally varies with system flow; and the inherent characteristic curve may not reflect the installed curve.

The installed characteristic is obtained when the valve is installed in a system; the pressure drop across the valve is a function of the pressure drops in the system. Thus, the installed characteristics depend upon both the inherent characteristic of the valve and the system flow characteristic. This is important and should be considered when problems are evaluated because there may be significant differences between the installed and the inherent characteristic curves.

The three most common control valve characteristics are linear, quick-opening, and equal-percentage. Another type that may be encountered is parabolic.

## LINEAR CHARACTERISTIC

A linear flow characteristic relfects a linear relationship between the flow rate through the valve and the valve-stem position; for instance, at 20 percent of valve-stem travel, the valve will pass 20% of its rated flow. A curve that depicts a linear characteristic is provided in Figure 33-5-6. The linear characteristic can be demonstrated mathematically from Equation 33-5-1.

$$Q = ky \qquad \text{Equation 33-5-1 (Equation = Eq.)}$$

where:

Q = flow.
y = valve opening.
k = a constant.

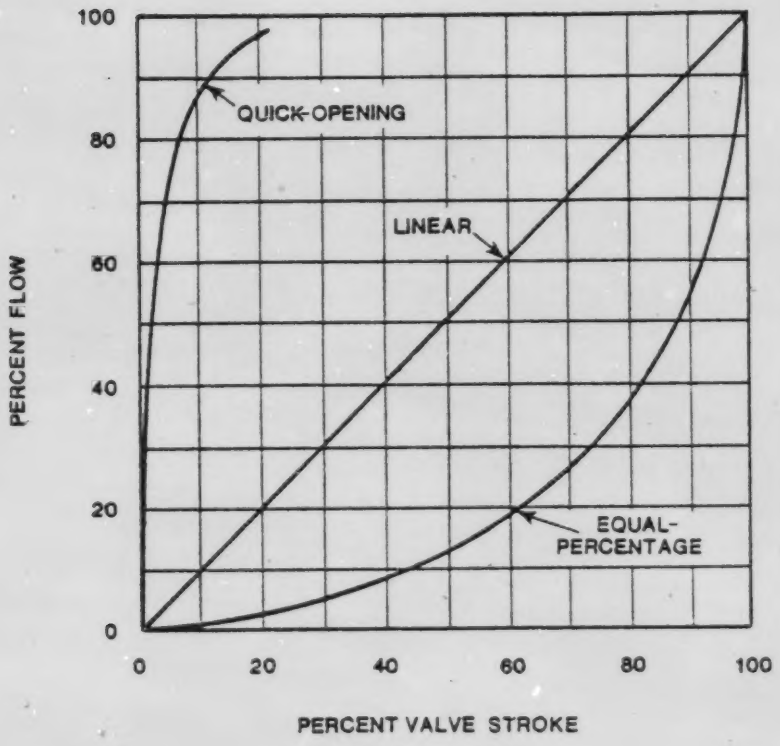



Figure 33-5-6. Control-valve characteristic curves for quick-opening, linear, and equal-percentage characteristics.

The valve-flow characteristic can provide an indication of valve gain – the sensitivity of valve flow to change in stem travel. The linear characteristic indicates a constant gain. Normally, if the load changes in the system are linear, the control valve selected for the system should be linear. However, system pressure drops could cause the system to have an installed characteristic different from linear.

## QUICK-OPENING CHARACTERISTIC

A quick-opening characteristic provides a large increase in flow resulting from a small initial movement of the valve stem and then a smaller increase during upper stem travel. The curve in Figure 33-5-6 represents a quick-opening characteristic.

The curve for a quick-opening characteristic indicates a high initial valve gain with a subsequent lower gain at upper stem travel. Usually, a control valve with this characteristic is utilized in on-off or two-position control systems in which valve movement from open to close must be quick. The quick-opening characteristic normally is not defined mathematically.

## EQUAL-PERCENTAGE CHARACTERISTIC

The equal-percentage characteristic gives an equal percentage change in flow rate for an equal change in valve-stem position. This characteristic curve is also illustrated in Figure 33-5-6. The equal-percentage characteristic is an exponential function, and the curve will plot a straight line when graphed on semilogarithmic graph paper (Figure 33-5-7).

An equal-percentage valve is designed to function between a minimum and maximum flow rate, which is termed "rangeability" when expressed as a ratio. Rangeability is expressed mathematically by Equation 33-5-2.

$$R = \frac{Q_{max}}{Q_{min}} \qquad \text{Eq. 33-5-2}$$

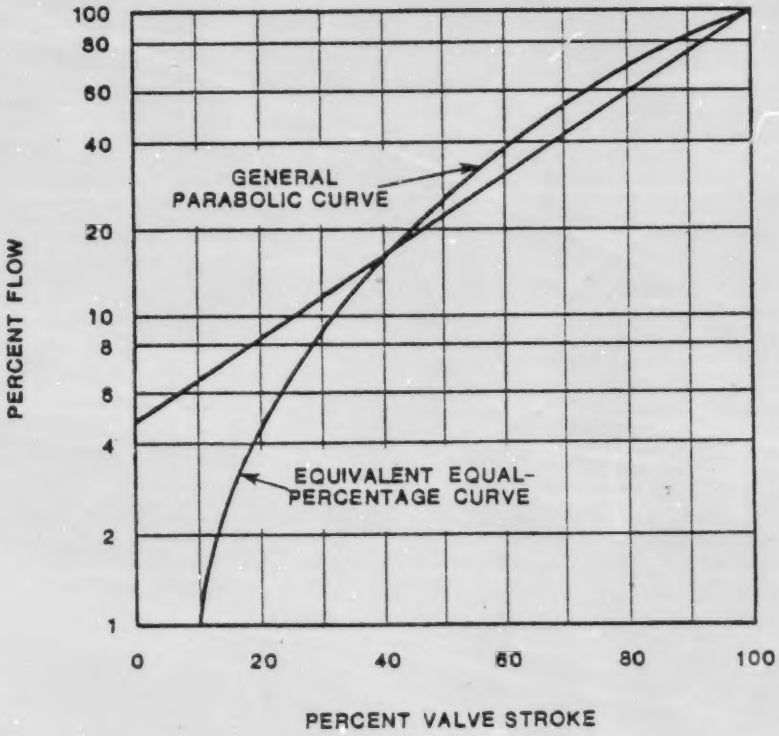



Figure 33-5-7. Parabolic characteristic curve presented with an equivalent equal-percentage characteristic curve on semilogarithmic graph paper.

where:

R = rangeability.

$Q_{max}$ = maximum flow rate.

$Q_{min}$ = minimum flow rate.

Equation 33-5-3 is a general mathematical expression for an equal-percentage characteristic in terms of effective area versus valve opening.

$$Q = be^{ay} \qquad \text{Eq. 33-5-3}$$

where:

Q = flow.
y = valve opening.
e = base of natural logarithms.
a,b = constants.

PARABOLIC CHARACTERISTIC

Many control valves still in use have port openings similar to a straight-sided V. The characteristic of these valves approaches the equal-percentage characteristic and is commonly referred to as a "modified-parabolic characteristic. A curve for this type of characteristic is illustrated in Figure 33-5-6.

The port area versus valve opening is expressed by Equation 33-5-4.

$$Q = ky^2 \qquad \text{Eq. 33-5-4}$$

where:

Q = flow.
y = valve opening.
k = constant.

Both the equal-percentage and parabolic characteristics display low valve gains in the initial opening regions; however, as the valve-stem travel increases, valve gain increases significantly. One advantage of the low gain at the initial opening of the valve is that the range of normal flow will

function closer to 50 percent or greater valve stroke, and the high fluid velocities that occur at conditions close to shut-off will not prevail. These high velocities can cause excessive erosion of valve seats.

## CONTROL-VALVE CHARACTERISTIC SELECTION

Proper selection of a control valve requires matching of the valve characteristic to the system characteristic. In this way, control stability can be achieved. Performance of this function for a specific system requires a good dynamic analysis. However, when a dynamic analysis has not been performed and there is doubt as to which characteristic to select, experience has shown that an equal-percentage characteristic is the best choice.

## CONTROL VALVE SIZING

Control valves are sized for two general purposes — economics and control stability. Where economics is concerned, if the valve is too small, it will not allow the required flow to pass through and, therefore, will require that the valve be replaced. Conversely, if the valve is too large, it will allow the required flow to pass through; but it will be more expensive, and throttling will occur close to the shut-off point, causing high fluid velocities across the valve seat which can cause excessive erosion.

Again, if the valve is too small, it will not pass the required full flow rate, and the controllable flow range will be reduced. If the valve is too large, its full control

range will not be used; and it will be throttling close to the shut-off point.

The acceptable method of valve sizing is the flow coefficient ($C_v$) approach. The $C_v$ value expresses the relationship between the flow rate through the valve, pressure drop across the valve, and specific gravity of the fluid.

## PRESSURE DROP ACROSS THE VALVE

The pressure drop across a control valve is the most uncertain of the sizing factors – primarily because the control valve does not define the pressure drop across it. Pressure drop results not only from the valve, but also from the system. For some applications, such as pressure reducing, the pressure drop across the valve may be determined quite accurately. However, if the valve is installed in a system that contains long piping, valves, and many fittings, the pressure drop may have to be estimated.

Because of lower fluid velocity at low flow rates, the pressure loss due to piping and fittings is less than at higher flow rates. This, in turn, causes increased pressure at the control-valve inlet and also decreases the required pressure at the valve outlet. Consequently, the pressure drop across the valve is greater at low flow rates than at higher flow rates. When the sizing formula is employed, a greater pressure drop across the valve requires a smaller capacity valve; therefore, valve size must be calculated at maximum flow rate and minimum pressure drop.

FLOW RATE

For valve sizing, the maximum flow rate should be considered. This figure should be realistic and carefully related to the available pressure drop, as previously noted. The flow rate should reflect the required maximum flow, not the valve capacity. To provide a margin of safety, a safety factor, which usually is 25 to 60 percent, is added to modify the maximum required flow rates employed in the calculation of valve size. The modified flow rate can be determined from Equation 33-5-5.

$$Q_{mod} = k_{saf} Q_{max} \qquad \text{Eq. 33-5-5}$$

where:

$Q_{mod}$ = modified flow rate of valve in gallons per minute (gpm).

$k_{saf}$ = safety factor.

$Q_{max}$ = maximum flow rate required through valve.

EXAMPLE

Given: A required maximum flow rate is 200 gallons per minute, and a safety factor of 30 percent is desired.

Find: The modified flow rate of the valve to be chosen for this application.

Solution: Use Equation 33-5-5:

$$Q_{mod} = k_{saf} Q_{max}$$
$$= (1.30)(200)$$
$$Q_{mod} = 260 \text{ gpm.}$$ (The valve should have at least this capacity.)

NOTE: 30% was added to 100% to give the total increase of 30% in the valve capacity.

## SPECIFIC GRAVITY

Specific gravity is another factor that influences valve sizing. However, when the basic sizing equation is employed, the actual specific gravity of liquids need not be known. For example, the use of a solution assumed to have a specific gravity of 0.8 when it actually was 0.7 would result in an error of less than 5 percent in determination of valve capacity. Specific-gravity values normally can be found in engineering handbooks.

## VALVE-FLOW COEFFICIENT

Valve sizing is accomplished through the use of the valve-flow coefficient ($C_v$), which can be determined from the values of the maximum fluid flow rate, specific gravity, and minimum pressure drop across the valve.

$C_v$ is a capacity coefficient and is defined as the number of U.S. gallons-per-minute of water at 60°F that will flow through a wide-open valve with a pressure drop of 1 psi across the valve. Equation 33-5-6 is the basic

$C_v$ equation for liquids.

$$Q = C_v \sqrt{\Delta P/G} \qquad \text{Eq. 33-5-6}$$

where:

Q = liquid flow rate, gallons per minute.
$C_v$ = valve-flow coefficient.
$\Delta P$ = pressure drop across the valve, psi.
G = specific gravity of the liquid.

Although $C_v$ is defined in terms of water flow, it can also be employed with sufficient accuracy for other noncompressible fluids.

## DETERMINING VALVE SIZE

After the maximum flow rate, specific gravity of the liquid, and minimum pressure drop across the valve are determined, the $C_v$ can be calculated and compared to values on manufacturer's tables to determine the required valve size. Table 33-5-1 is a representative table.

TABLE 33-5-1.

APPROXIMATE $C_v$-VALUES FOR VALVES OF COMMON SIZE.

| Valve Size (in) | $C_v$ | Valve Size (in) | $C_v$ |
|---|---|---|---|
| 3/4 | 10 | 3 | 110 |
| 1 | 14 | 4 | 190 |
| 1 1/2 | 30 | 6 | 430 |
| 2 | 50 | 8 | 820 |

EXAMPLE

Given: The maximum flow rate in a system is 330 gpm, and the available pressure drop across the valve at maximum flow is 70 psi. Allow a safety factor of 30 percent.

Find: The size of control valve required to control the flow of a liquid that has a specific gravity of 0.94.

Solution: Use Equation 33-5-6 and Table 33-5-1 as follows:

$$Q = C_v \sqrt{\Delta P/G}$$

$$(1.30)(330) = C_v \sqrt{70/0.94}$$

$$429 = 8.63\ C_v$$

$$C_v = 49.7.$$

Compare this $C_v$ value to the valve sizes in Table 33-5-1: Observe that for a $C_v$ of 49.7, a 2" valve is required.

A similar process can be employed to determine valve sizes for the control of gas, steam, and vapor. The applicable $C_v$ equations are available from valve manufacturers or from appropriate handbooks.

## VALVE ACTUATORS

Almost all valves must be physically operated by an actuator – mechanical, electrical, hydraulic or pneumatic.

Mechanical actuators include the handwheel, the chain wheel for valves in inconvenient positions, and the gear head.

Electric motors allow remote operation of valves. Such motors are usually of the high-speed type, but their speed is reduced by a gear train that increases torque for tight valve closure.

Solenoid-operated valves are snap acting and normally are limited to small sizes. Solenoid valves are especially popular in complex control systems.

In hydraulic actuators, a piston translates signal pressure into valve-stem motion. One side of the piston has the pressure increased to it while the other side is reduced or bled off. The force and travel needed to operate the valve is attained by the variation of the cylinder size to agree with the available hydraulic pressure.

The pneumatic actuator is the most commonly used type for control-valve operation. Basically, it consists of a synthetic-rubber diaphragm and a calibrated spring. The spring and diaphragm normally are selected to meet the requirements of the application. Its operation is fairly simple: Air pressure that acts on the top of the diaphragm

opposes the spring pressure that acts on the bottom of the diaphragm. Full travel of the valve stem is caused as air pressure is changed from 3 to 15 psi; or in some cases, from 6 to 30 psi. Valve-stem position can be determined from a graph similar to that illustrated in Figure 33-5-8, which relates valve-stem position to the air pressure being applied to the diaphragm. A typical pneumatic actuator is depicted in Figure 33-5-9.

Pneumatic actuators may be direct or indirect acting. For a direct-acting actuator, increased air pressure causes the stem to extend from the housing, and an indirect-acting

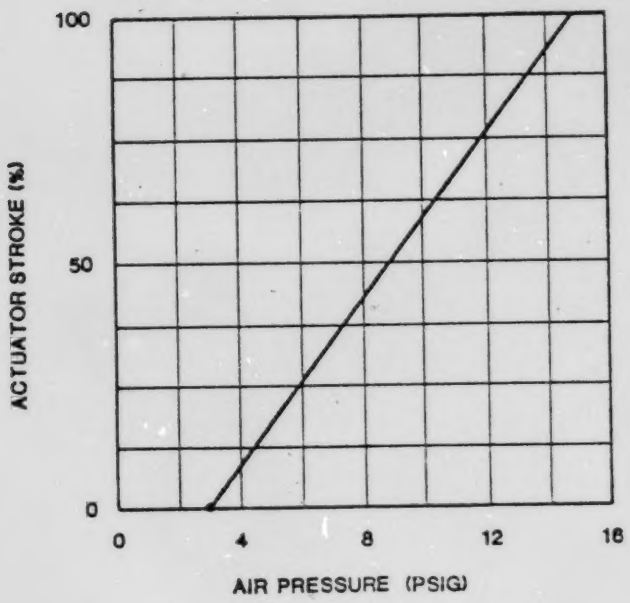



Figure 33-5-8. Typical actuator stroke versus air pressure curve.

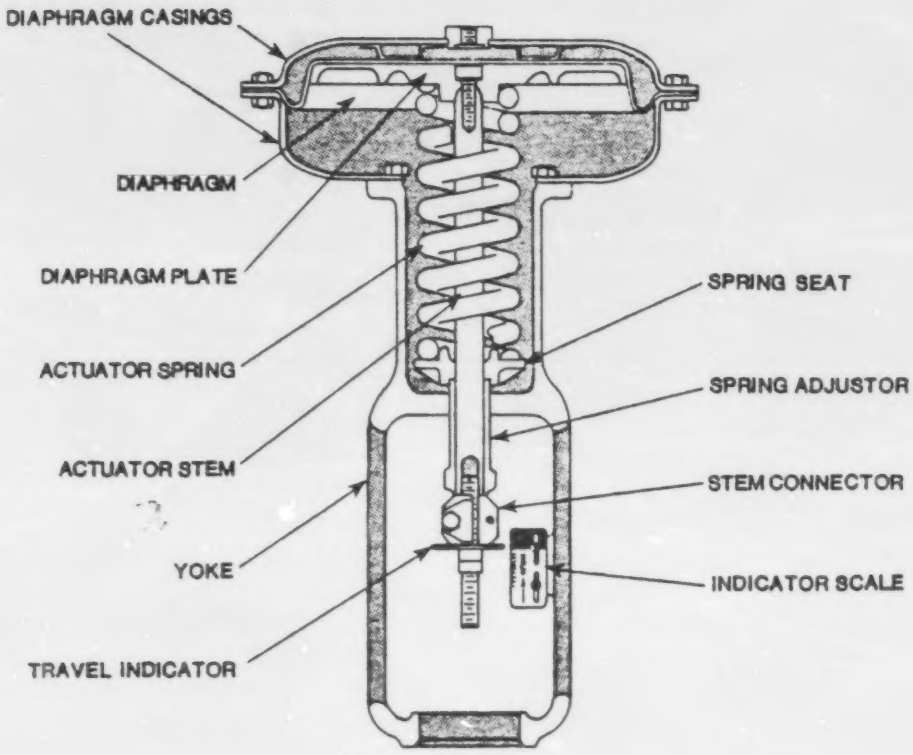



Figure 33-5-9. Typical control-valve pneumatic actuator.

actuator causes the stem to retract into the housing. Both types are illustrated in Figure 33-5-10.

The pneumatic actuator is attached to the control by a yoke, and the actuator stem is attached to the valve stem. The valve action – the direction in which the valve plug moves as the air pressure on the diaphragm increases – is determined by the diaphragm stem movement. If increasing

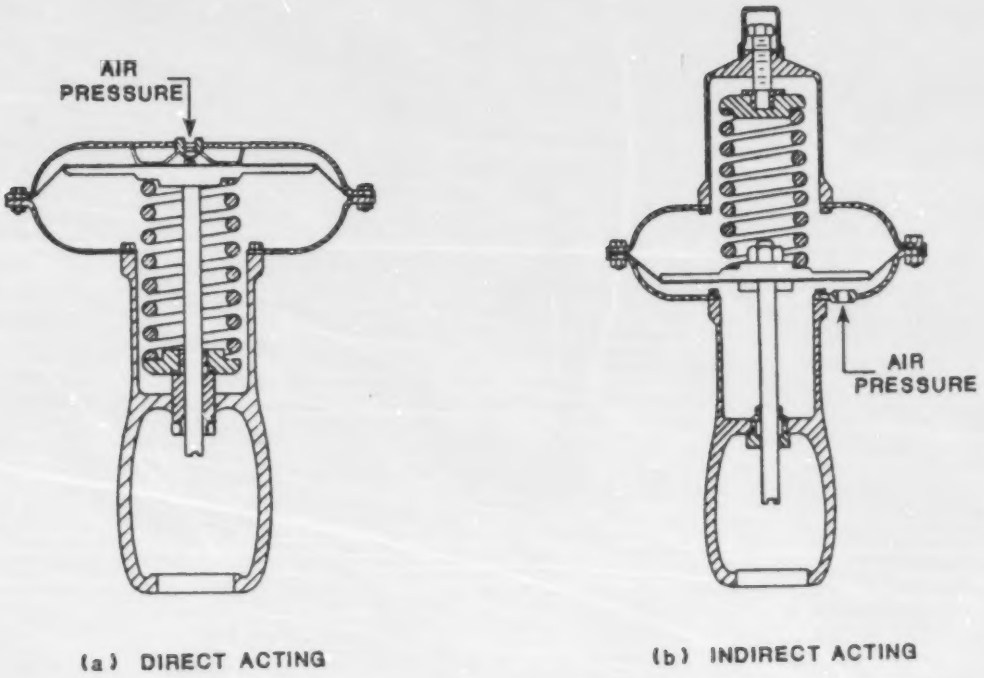



Figure 33-5-10. Control-valve pneumatic actuators.

air pressure causes the valve to close, the valve action is defined as "air-to-close." If increasing air pressure causes the valve to open, the valve action is defined as "air-to-open." The combination of valve action and actuator action can provide four types of operation – (1) direct acting air-to-close, (2) reverse acting air-to-close, (3) direct acting air-to-open, and (4) reverse acting air-to-open.

## CONTROL-VALVE POSITIONERS

When the stem of a proportioning control valve cannot be positioned accurately, or when the controller-output signal cannot operate the control valve, a valve positioner is needed. Basically, the valve positioner must measure the controller-output signal and the valve-stem position, compare them, and then provide the necessary power to operate the valve to bring the stem to the position called for by the controller. This may be done in one of two ways – by deflection balance or by force balance.

The stem of a proportioning-type control valve ideally should position at 0.002 to 0.003" of the position called for by the controller-output signal, whether that signal is air pressure, hydraulic pressure, or an electrical voltage or current.

## EXERCISES

1. Prepare a one-page theme concerning the importance of the valve safety factor.
2. Prepare a one-page statement on the importance of control valves.

## MATERIALS

1 Fisher globe control valve (any of the following models: EC, EAC, ES, or EAS).
1 Electric hand drill, 3/8" or larger.
Assorted drill bits for drilling metal. The sizes of bits required depend upon the model of valve; refer to Table 33-5-2.

## PROCEDURES

### DISASSEMBLY, REASSEMBLY, AND INSTALLATION OF FISHER GLOBE CONTROL VALVE (MODELS EC, EAC, ES, AND EAS)

WARNING: If this procedure is performed while the valve is connected in a process system, the valve must be isolated from the system and all pressure must be released from the body and actuator before disassembly.

DISASSEMBLY

1. After the actuator is disconnected and taken off the body, remove the nuts or cap screws from the bonnet flange. (Refer to Figure 33-5-11).
2. Lift off the bonnet, along with the valve plug and stem.
3. Loosen the packing flange nuts, and separate the valve plug and stem from the bonnet. If the stem needs replacing, drive out the groove pin, and unscrew the stem. If the valve plug needs replacing, always replace the entire valve plug and stem assembly. CAUTION: Never

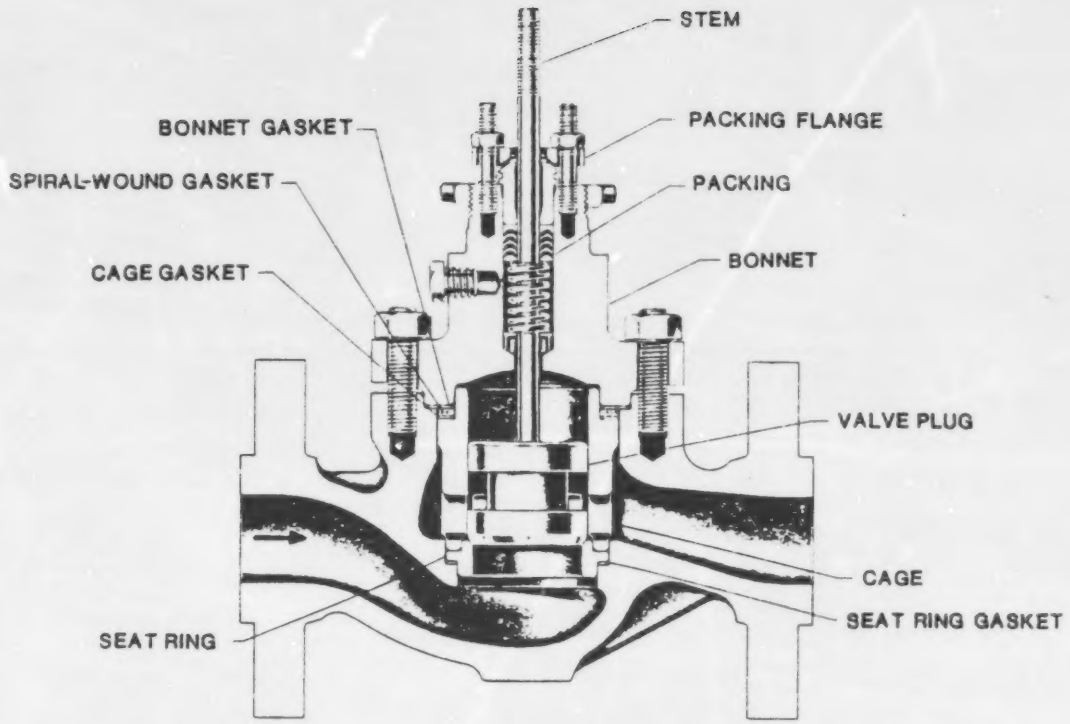



Figure 33-5-11. Typical Fisher globe control valve.

use an old stem with a new valve plug. The use of an old stem requires that a new groove-pin hole be drilled through the stem, thereby weakening the stem.

4. Lift out the cage and gaskets. For restricted trim, also remove the cage adaptor and seat-ring adaptor.
5. Lift out the seat ring and gasket. For composition seats, remove the disc retainer, disc seat, and disc.
6. If the instructor wishes the internal parts of the bonnet disassembled, refer to the manufacturer's manual for packing replacement and for bellows seal replacement before proceeding.

REASSEMBLY

1. Clean all gasketed surfaces, and use all new gaskets for assembly.
2. For restricted trim, replace the seat-ring adaptor gasket and adaptor.
3. Install the seat-ring gasket and replace the seat ring. If a composition seat is being used, assemble it by inserting the disc into the disc retainer; and slip this combination over the disc seat.
4. Install the cage on top of the seat ring. Be sure that the cage slips onto the seat ring properly. Any rotational orientation of the cage with respect to the body is acceptable.
5. For full-size trim, place cage gasket, spiral-wound gasket, and bonnet gasket on the shoulder of the cage.
6. For restricted trim, place the cage gasket, sprial-wound gasket, and another cage gasket on the shoulder of the cage. For 2" x 1" angle and 1 1/2" x 1" globe bodies, a body adaptor gasket is required between the cage adaptor and body. Insert the cage adaptor, and place the bonnet gasket on the adaptor.
7. If a stem is to be assembled to the valve plug, screw the stem into the valve plug until it wedges tight at the end of the valve-stem thread.
8. For Designs EC and EAC, determine drill size and location from Table 33-5-2, and drill the groove-pin hole through the plug and stem assembly.
9. For Designs ES and EAS, determine drill size from Table 33-5-2. Locate the pilot hole in the valve plug; and continue drilling through the plug and stem assembly.

TABLE 33-5-2. GROOVE-PIN DATA.

| VSC* Size, in | Designs EC and EAC | | Designs ES and EAS |
|---|---|---|---|
| | Drill Size in | "D" Dimension in | Drill Size in |
| 3/8 | 3/32 | 5/8 | 3/32 |
| 1/2 | 1/8 | 3/4 | 1/8 |
| 3/4 | 3/16 | 1 | 3/16 |
| 1 | 1/4 | 1 1/8 | 1/4 |
| 1 1/4 | 1/4 | 1 3/8 | 1/4 |

*Valve-stem connection

NOTE

Micro-Flute, Micro-Form, and Micro-Flute (composition seat sith 1/2", 3/4", or 1" orifice sizes and all metal-seat) valve plugs use 3/8" VSC drill size shown above. Composition seat Micro-Flute valve plugs with 1/4" or 3/8" orifice size use a threaded retainer instead of a groove pin.

Remove any burrs caused by drilling, and drive in the groove pin to lock the assembly.

10. Install the valve-plug assembly in the cage.
11. Mount the bonnet on the body.
12. Tighten the bonnet-to-body bolts to the recommended bolt torques given in Table 33-5-3. (Follow accepted bolting practices, and lubricate bolts.) Proper tightening of the bonnet bolts accomplishes two purposes:
    a. The spiral-wound gasket compresses enough both to load and to seal the seat-ring gasket.
    b. The outer portion of the top gasket compresses so that the bonnet-to-body joint forms a seal.

NOTE: Spiral-wound gasket boltup characteristics are such that tightening of one bolt may loosen an adjacent bolt. This will occur on subsequent tightening of all the bolts until the bonnet-to-body seal is made. This requires several trials on each bolt until the nut does not turn at the given torque.

13. Mount the actuator on the bonnet, and make up the stem connection.

TABLE 33-5-3. RECOMMENDED BOLT TORQUES.

| Body Size (inches) | Recommended Bolt Torque (ft·lb) |
|---|---|
| 1/2, 3/4, 1, 1 1/4 | 100 |
| 1 1/2 | 80 |
| 2 | 80 |
| 2 1/2 | 100 |
| 3 | 130 |
| 4 | 190 |
| 6 | 400 |

INSTALLATION

1. Before installing an easy-e body, inspect for any shipment damage and for any foreign material that may have collected.
2. Blow out all pipelines to remove pipe scale, chips, welding slag, and other foreign materials.

3. Install the valve in such a manner that flow through the body will be in the direction indicated by the flow-direction arrow on the body.
4. Install the valve using accepted piping practices. For flanged bodies, use a suitable gasket between the body and pipeline flanges. (Before installing welding-end bodies having composition seats, remove the trim to avoid damage to elastomer parts from heat generated by welding.)
5. Control valves with an easy-e body can be installed in any position, but the normal method is with the actuator vertical above the body.
6. If continuous operation is required during maintenance and inspection, install a conventional three-valve bypass around the body.
7. Do not install the valve in a system in which the working pressures exceed those specified for the valve.

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Kirk, Franklyn W. and Nicholas, Rimboi, R. Instrumentation. 3rd ed. Chicago: American Technical Society, 1975.

Power Plant Steam and Mechanical Fundamentals. Section 19, "Valves, Traps and Piping." Chicago: Commonwealth Edison Company, 1976.

1. Define the following terms:
   a. Globe control valve.

   b. Butterfly control valve.

   c. Ball control valve.

   d. Linear characteristic.

   e. Quick-opening characteristic.

   f. Equal-percentage characteristic.

   g. Parabolic characteristic.

   h. Valve-flow coefficient.

   i. Valve actuator.

   j. Valve positioner.

2. Describe the operation of direct- and reverse-operating pneumatic valve actuators.

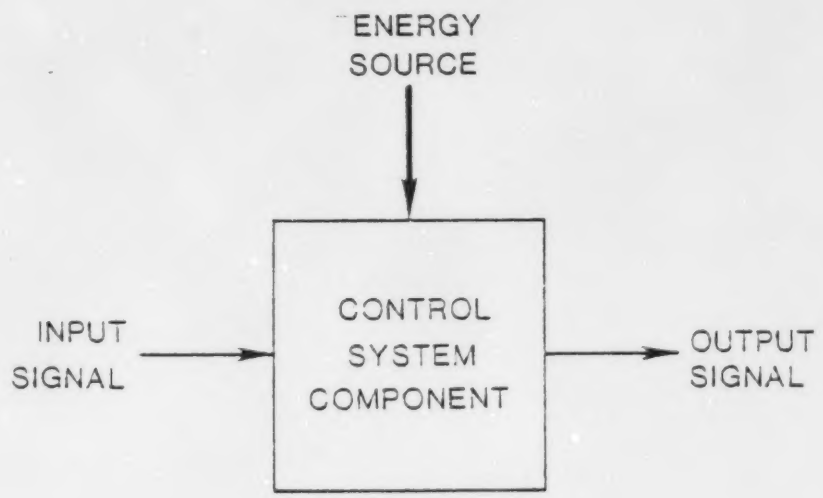
3. Draw the following typical control valve characteristic curves.
   a. Quick-opening.
   b. Linear.
   c. Modified parabolic.
   d. Equal-percentage.

4. From the $C_v$ values in Table 33-5-1, determine the correct size of the control valve for the following application:
   - Maximum flow is 425 gallons per minute.
   - Minimum pressure drop across the valve is 90 psi.
   - Specific gravity of the liquid is 0.92.
   - Utilize a safety factor of 25 percent.

# NUCLEAR TECHNOLOGY

## MODULE 33-6

PROCESS CONTROL CHARACTERISTICS




CONTROL SYSTEMS I
COURSE 33

ORD CENTER FOR OCCUPATIONAL RESEARCH AND DEVELOPMENT

# COURSE MODULES

CONTENTS

COURSE 33 CONTROL SYSTEMS I


MODULE 33-1 Introduction to Block Diagrams
MODULE 33-2 Input/Output Devices
MODULE 33-3 Control System Theory
MODULE 33-4 Pneumatic Control Mechanisms
MODULE 33-5 Control Valves
MODULE 33-6 Process Control Characteristics



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# INTRODUCTION

Automatic control of processes requires the use of many different types of hardware and hardware combinations. A glance at a catalog that exhibits process equipment available as standard items will reveal that the assortment of devices for the use of process control is great. Complexity of the task of choosing the proper combination of components to be used in a particular process is increased because a vast number of specialty items are also available. Given this situation, it would seem that the probability of selecting the exact combination of hardware best suited to control a particular process is somewhat low. This is especially true when one considers the fact that the number of process characteristics that determine the instrument systems necessary to implement optimum control is as great as the number of various systems available.

Process characteristics can be analyzed and associated with those required for specific control-system applications. In this way, instruments can be accurately matched to a particular process, thus achieving compatibility. This module introduces the procedures by which process dynamic qualities are determined and defined. The means by which this information is employed to adapt control systems to a process to achieve optimum control will be studied.

## MODULE PREREQUISITES

The student should have completed Course 3, "Principles of Process Instrumentation"; Course 6, "Instrumentation and Control of Reactors and Plant Systems"; and all previous modules of this Course.

## OBJECTIVES

Upon completion of this module, the student should be able to:

1. Define the following terms:
   - Self-regulation.
   - Stability.
   - Damping.
   - Gain.
   - Capacity (process).
   - Capacitance (process).
   - Dead time.
   - Lag time.
2. Correctly use the terms in paragraph 1 to describe the utilization of the proper control mode or control-mode combinations for optimum control of a process.
3. Describe the relationship between input and output with respect to time and amplitude of a automatic-feedback, three-mode controller.
4. List an example of at least one type of process in a nuclear power plant that can be controlled by the following control modes or control-mode combinations:

On-off.
Proportional.
Proportional plus reset.
Proportional plus derivative.
Proportional plus reset plus derivative.

## PROCESS TRANSFER FUNCTIONS

The purpose of a control system is to maintain a balance between the supply and demand on a process. The dynamic characteristics of the process under control are factors that determine the criteria of the associated control systems. Before optimum control can be achieved, the behavior of a process as a result of a variation in a specific input must be determined (Figure 33-6-1). The relationship between the input and the output of a process is defined as the "transfer function" and is the most important factor to be considered in the implementation of control.

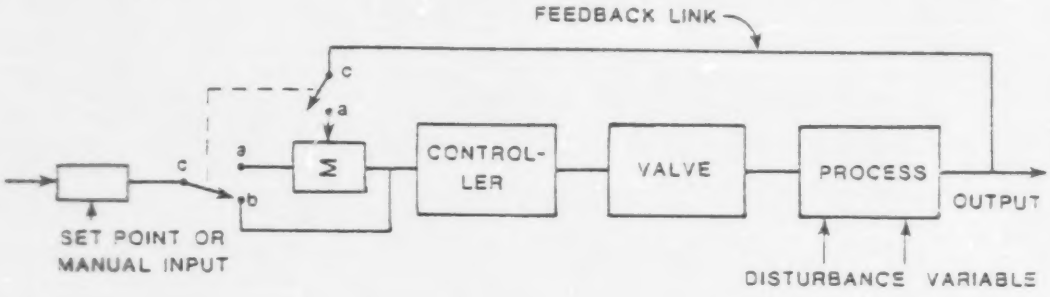



Figure 33-6-1. Feedback control system in open-loop (manual) control.

## PROCESS STABILITY

With an automatic feedback control system in open loop control as shown in Figure 33-6-1 (switch ac open), the process should be stable. That is, the process will have a natural tendency to return to a steady-state condition after a

change in input and to remain so until another input variation is introduced into the system. In order to achieve this condition, the system must be free of independent sources of input energy. Consider the block diagram in Figure 33-6-2, which represents the control system in Figure 33-6-1. A variation in input will cause a change in output. The transfer function of the process must be passive in order to produce stability, which follows the input variation.

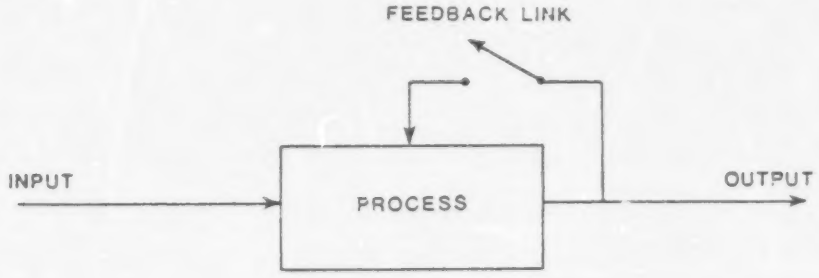



Figure 33-6-2. Closed-loop process in manual control.

A response of process output to input variation is depicted in Figure 33-6-3. The process measurement, after a

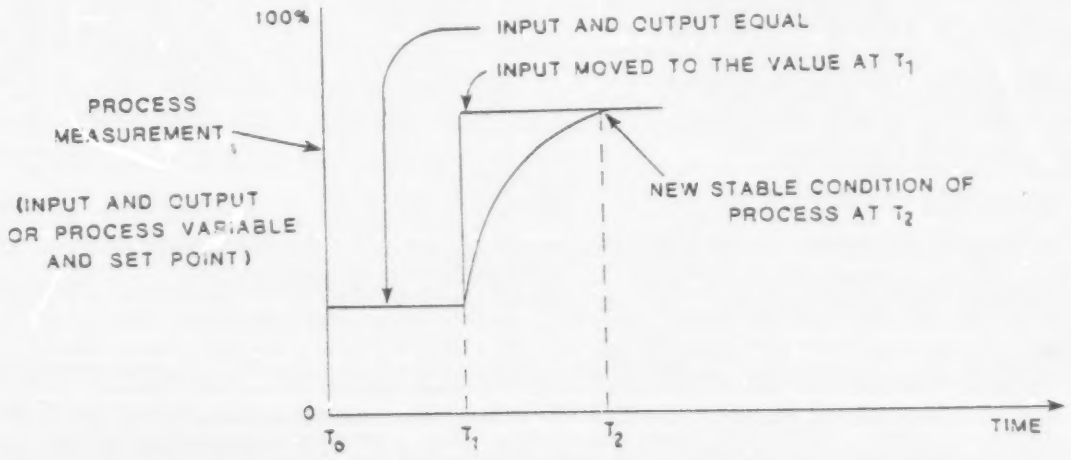
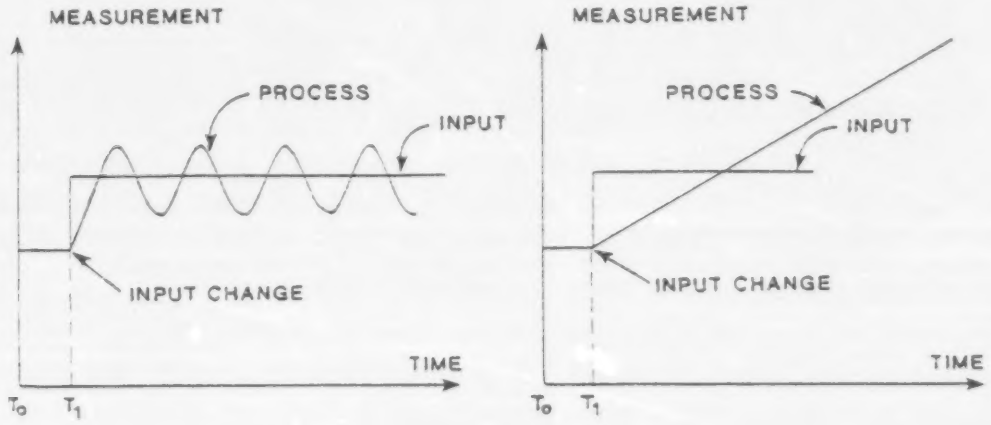



Figure 33-6-3. Process reaction to input variation.

time follows the input to a new stable value at $T_2$. The difference in $T_2$ and $T_1$ results in process damping and is caused by the transformation or absorption of energy in the process. If $T_2 = T_1$, the process would move to a new value as soon as it encounters an input disturbance.

If a process is not self-damping, it will not reach a stable condition after a variation input, but will continue to change. Examples of this are illustrated in Figure 33-6-4.




(a) Sustained Oscillation After Input

(b) Continuous Change After Input

Figure 33-6-4. Processes that are not self-regulatory.

In Figure 33-6-4a, the process reaction to a change in input is such that the process continues to oscillate. In Figure 33-6-4b, the process continues to change at a constant rate. Oscillation may occur after a change in process input, but will be damped by the process, as indicated by Figure 33-6-5.

Most processes found in nuclear power plants and all that are controlled by conventional feedback control have transfer functions as depicted in Figure 33-6-5. The number

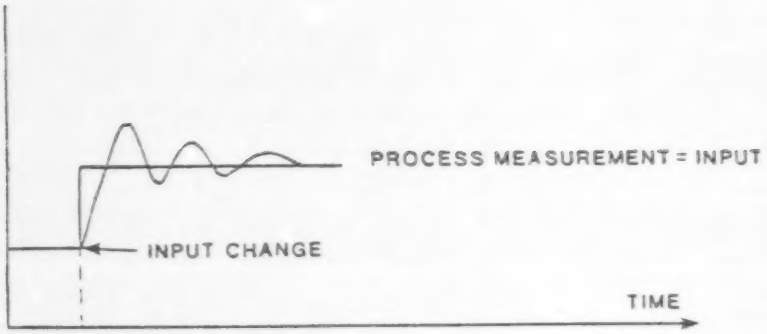



Figure 33-6-5. Process producing damped oscillation.

of oscillations may be more or less than indicated, but certainly, a stable process will follow an input variation.

The process that produces the transfer function in Figure 33-6-4b has independent sources of energy. An increase in input (added energy) produces an increase in output, which, by chemical reaction or other means, creates an additional increase in energy input. Such processes are difficult, if not impossible, to control by feedback control applications.

## PROCESS DYNAMIC PROPERTIES

By observing the dynamic properties of a process as displayed by the transfer function, the technician can determine the gain and phase shift.

### Phase Shift

The phase shift or time-response relationship between input and output of a process is a measure of the time elapsed

between a change in input and the measurement of a corresponding change in output. The total elapsed time is a measure of both the response time of instruments involved in process measurement and the response time of the process itself. The phase shift of a given process is a reliable index of the degree of difficulty that may be expected when a control system is implemented for that process.

Dead Time

The "dead time" of a process is a measure of the time required for the process to react to a change in input energy. Dead time is also referred to as "first-order lag" or "transfer lag." The time required for energy transfer within the process produces dead time and is dependent upon the type of process. For example, the flow process depicted in Figure 33-6-6 has little dead time because very little energy can

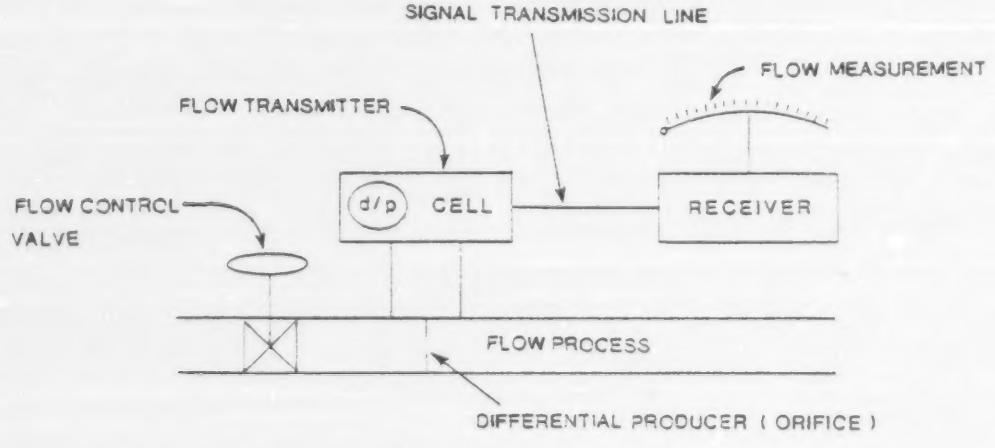



Figure 33-6-6-. Flow process and dead time.

be stored in the process. Thus, when a change in valve position occurs, the flow will change almost instantly.

Temperature processes have a larger capacity for energy storage, which results in a larger amount of dead time. Refer to the temperature process depicted in Figure 33-6-7. When the valve that controls steam flow to the heat exchanger alters the steam flow, a change in output temperature is not immediate. A transfer of energy from the steam to the coils must occur first, producing what is known as a "first-order lag." Energy then is transferred to the process from the

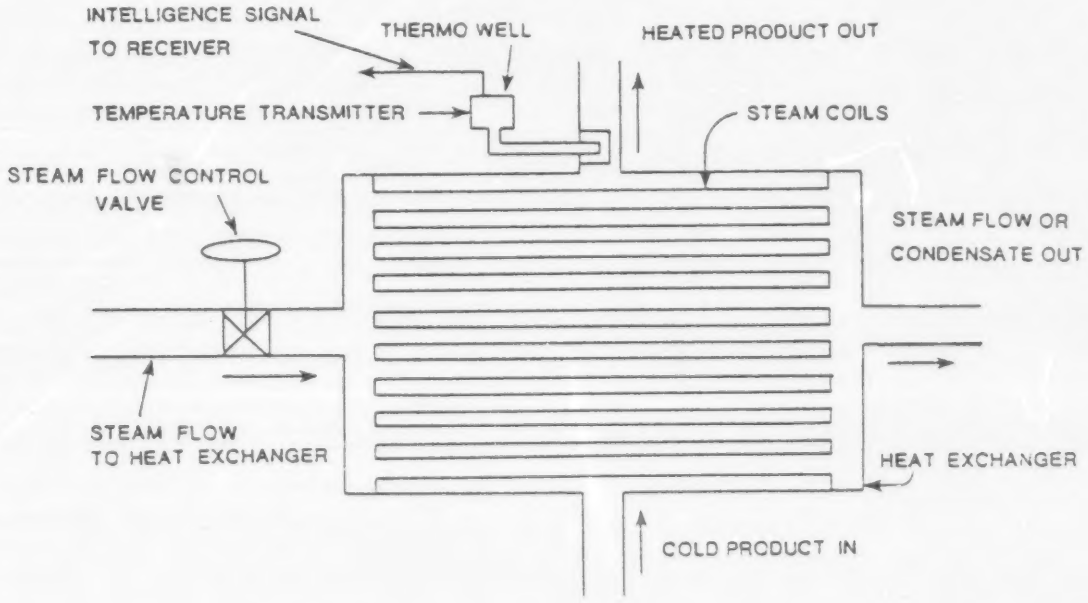



Figure 33-6-7. Temperature process and dead time.

coils of the heat exchanger. This energy transfer produces a "second-order lag." Total dead time of the process is the result of the first- and second-order lag times. Temperature processes usually are characterized by a high dead-time

factor. This is because of the thermal momentum of the process components such as the heat exchanger and the process material. Conversely, when the steam flow is reduced, heat in the coils must be removed by the product before the output temperature will decrease.

## Lag Time

"Lag time" is a measure of the time required for a primary element, transducer, or other measuring device to respond to a change in process conditions. The d/p cell in Figure 33-6-6 can respond very quickly to a change in pressure differential across the differential producer. The flow measurement is nearly simultaneous with actual valve flow. This is not the case in the temperature process of Figure 33-6-7, however, because heat energy is stored in the transducer element of the temperature transmitter, which is in contact with the process. Thermo wells, which commonly are employed in temperature processes, also contribute to the lag time. If the transmitter that monitors the process is remotely located from the receiver, as is usually the case, lag time will result from time required for signal transmission. However, lag time in signal transmission normally is significant only in pneumatic-instrument applications. In any case, care should be taken to reduce both lag time and dead time to the minimum possible values; this procedure will reduce the undesirable effects of phase shifts. Lag time and dead time can be reduced by proper instrument selection and utilization.

In most processes, dead time is the largest single contributing factor to the phase shift of the total process. A

process-reaction curve, which represents the transfer function of a given process, can be used to show the effect of total time lost (dead time plus lag time) in a process-control system (Figure 33-6-8).

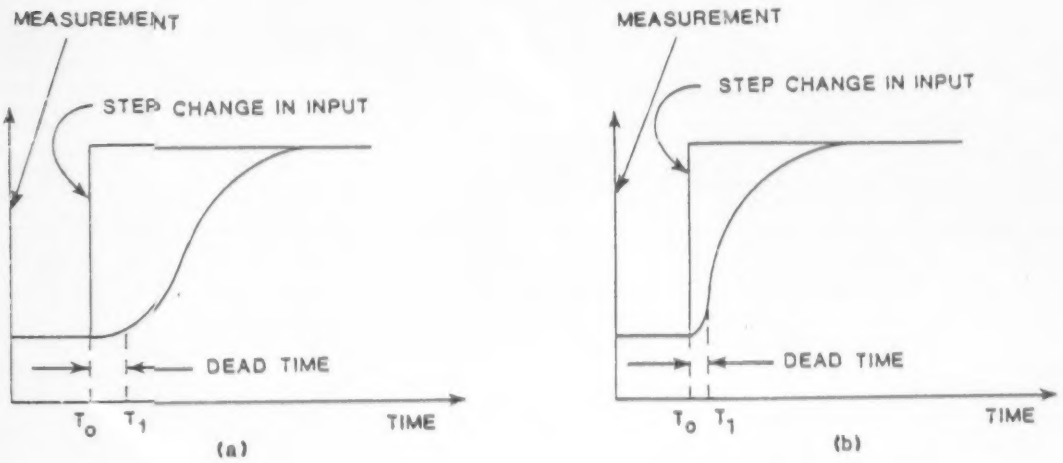



Figure 33-6-8. Process-reaction curves.

The process reaction curves in Figure 33-6-8 illustrate system response to a step change in input for a process with considerable dead time (Figure 33-6-8a) and with negligible dead time (Figure 33-6-8b). The temperature process in Figure 33-6-7 would produce a reaction curve similiar to that in Figure 33-6-8a, and the flow process in Figure 33-6-6 would produce a curve similar to that in Figure 33-6-8b.

Gain

The "gain" of a process is the ratio of a change in output to a corresponding change in input. Process gain can be

determined from a process-reaction curve developed by the introduction of a sudden change, called a "step change," into the process. The dynamic properties of the process are described by the system response to the step change. This type of graphic process evaluation is utilized for open-loop (manual) control systems. If the evaluation were made for a system in a closed-loop (automatic) control mode, the controller response would be added to the process response. The latter type of evaluation will be studied later.

In order that the gain of a process can be determined, input and output quantities must be expressed in the same unit. That is, the signal to the control element responsible for regulating the process input must be measured in the same units as the output signal from the transmitter responsible for measuring the process. A convenient method that may be utilized to determine process gain and to avoid the confusion that can result with instruments that have different signal units is to use the percent of full-scale signal levels. This procedure is referred to as "normalization of values." The process input is considered to be the signal level at the control valve, and the process output is taken as the signal that originates from the transmitter and that represents the condition of the process.

EXAMPLE

Find: The range of valve signal is 3-16 psi with a span of 12 psi. The range of the temperature transmitter is 0-200°F, with a span of 200°F. For a change of 0.5 psi in valve signal, the change in process measurement is 10°F.

Find: The gain of the process.

Solution: Use Equation 33-6-1:

$$\text{Gain} = \frac{\text{output change}}{\text{input change}} \qquad \text{Equation 33-6-1 (Equation = Eq.)}$$

Convert both input and output changes to percent of full-scale span:

$$\text{Percent of change} = \frac{\text{change}}{\text{span}} \times 100$$

$$\text{Input change} = \frac{0.5 \text{ psi}}{12 \text{ psi}} \times 100$$

$$\text{Input change} = 4.16\%.$$

$$\text{Output change} = \frac{10°\text{F}}{200°\text{F}} \times 100$$

$$\text{Output change} = 5.0\%.$$

$$\text{Process gain} = \frac{\text{output change}}{\text{input change}}$$

$$= \frac{5.0\%}{4.16\%}$$

$$\text{Process gain} = 1.20.$$

Obviously, a change in either the input-signal or output-signal parameters of the system will produce a different gain value for the process, as shown in the following examples.

EXAMPLE

Given: Valve range is 3-16 psi; span is 12 psi; and transmitter range is 50°F to 150°F. For a change of 0.5 psi in value signal, the change in process measurement is 20°F.

Find: The process gain.

Solution: Use Equation 33-6-1:

$$\text{Gain} = \frac{\text{output change}}{\text{input change}}$$

Convert both input and output changes to percent of full-scale span as the first Example:

$$\text{Input change} = \frac{0.5 \text{ psi}}{12 \text{ psi}} \times 100$$

$$\text{Input change} = 4.16\%.$$

$$\text{Output change} = \frac{20°\text{F}}{100°\text{F}} \times 100$$

$$\text{Output change} = 20\%$$

$$\text{Gain} = \frac{20\%}{4.16\%}$$

$$\text{Gain} = 4.80.$$

EXAMPLE

Given: Valve range is 3-15 psi; span is 12 psi; and transmitter range is 50°F to 150°F. For a change of 1 psi value signal, the process change is 20°F.

Find: The process gain.

Solution: Convert both input and output changes to percent:

$$\text{Input change} = \frac{1}{12} \times 100$$

$$\text{Input change} = 8.33\%.$$

$$\text{Output change} = \frac{20}{100} \times 100$$

$$\text{Output change} = 20\%.$$

$$\text{Process gain} = \frac{20\%}{8.33\%}$$

$$\text{Process gain} = 2.4.$$

The previous Examples illustrate the effect that valve and transmitter characteristics have on process gain. Additionally, the physical process itself will affect process gain. The level processes illustrated in Figure 33-6-9 have different values of gain because a given amount of flow variation will result in a different degree of level change in each tank. In Figure 33-6-9a, a given amount of flow variation into the narrow tank (Figure 33-6-9a) will produce a greater change in level than would result in the wide tank of Figure 33-6-9b. Although, the two tanks may have the same

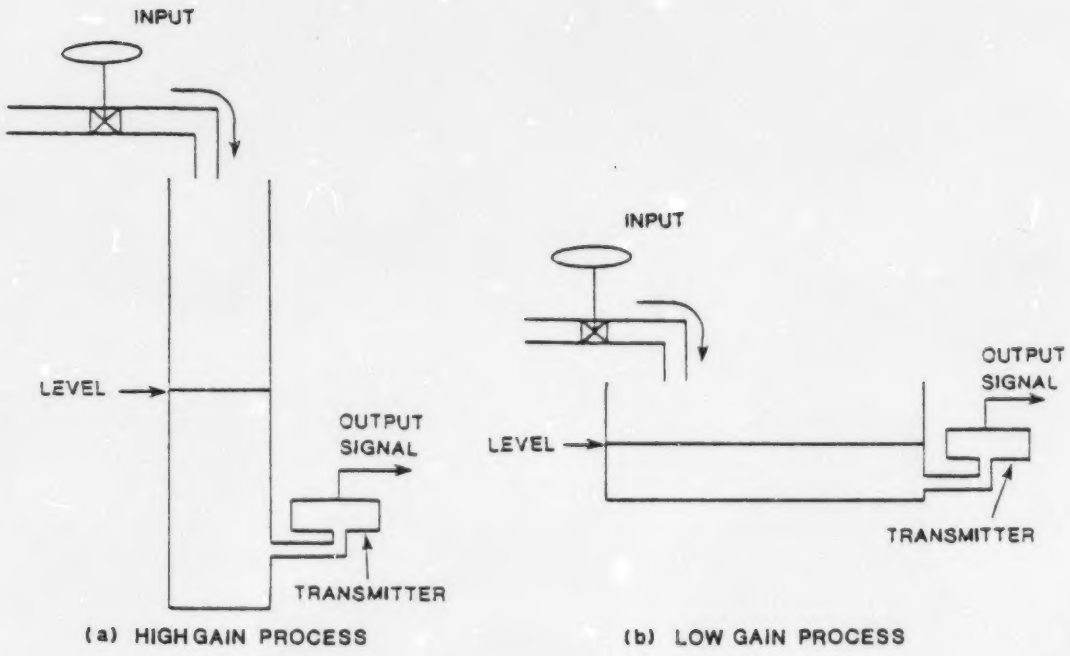



Figure 33-6-9. Physical characteristics and gain.

capacity, their individual capacitance is different. The difference in meaning of these two terms should be noted: Although, capacity refers to the volumetric characteristics of a process, capacitance refers to the energy-storage capability of a process. As the process capacitance increases, the energy-storage capability of the process increases, necessitating a larger change in input to achieve a given change in output for that particular process. An increase in capacitance, then, may be shown to produce a decrease in process gain, thus rendering the process less easily controllable. The process response curve in Figure 33-6-10 illustrates the effect of process gain and phase shift properties on a process-control system.

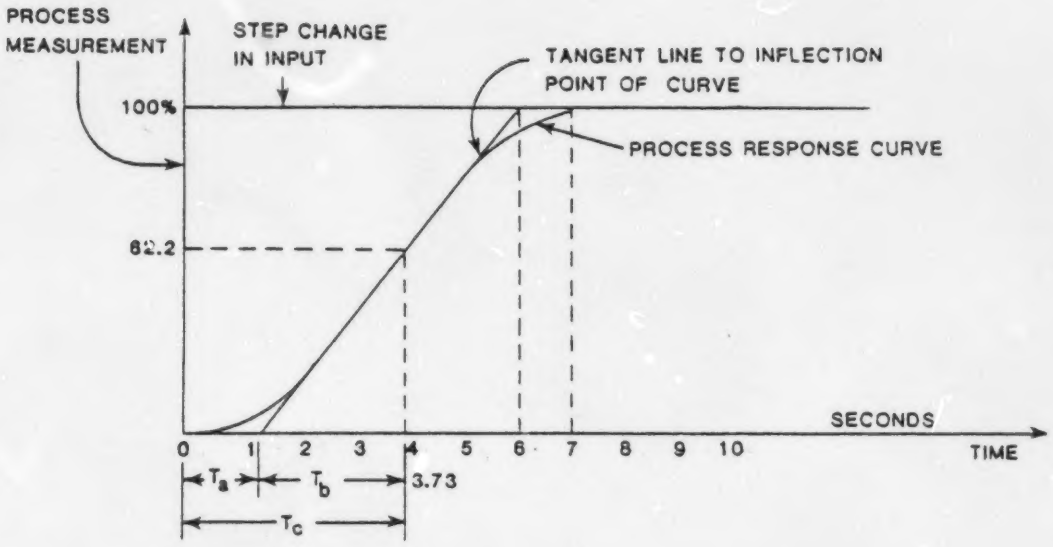



Figure 33-6-10. Process response curve.

PROCESS RESPONSE CURVES

The process response curve in Figure 33-6-10 is developed from the introduction of a step change into the open-loop system at $T_0$ with the reaction going to completion (100% value) in 7 seconds. A line drawn tangentially to the response curve intersects the time axis at T = 1 second. This value, denoted on the graph by $T_a$, is a function of the process dead time. The process time constant, measured at 62.2% of complete reaction, is determined by interpolation to be 3.73 seconds. This time-constant value is denoted by $T_c$ and is a measure of the rate at which the process will change for a given input value. The value denoted as $T_b$ is the difference between the values found for $T_a$ and $T_c$. The ratio $T_b/T_c$ is directly proportional to process controllability. When $T_a$

is small (minimal dead time), the ratio approaches unity, indicating relative ease of control. However, as $T_a$ increases, the ratio decreases; and control, thus, is more difficult due to increased process dead time.

## CONTROL MODES

### On-off

On-off, or two-position, controllers operate only when the process variable crosses the set point. The output has two states, zero or one hundred percent, meaning that the valve is either fully open or completely closed. Thus, energy is added to the process at extreme rates. However, recall that the purpose of a control system is to maintain a balance between supply and demand on a process. The process cannot be stable if material or product leaving a process is at a constant rate and if the the controller adds energy to the process by causing a valve to be either fully open or completely closed.

Figure 33-6-11 illustrates level being controlled in two different tanks by an on-off controller. Assume for initial conditions that the flow out is at a constant rate and that the control valve is closed. For this situation, the level will decrease, causing a deviation between set point and process variable (level). Any measurable deviation will cause the controller to open the control valve. This will add water to the tank, causing the level to increase until the process variable reaches set point, at which time the controller will close the control valve. Level then will decrease, and

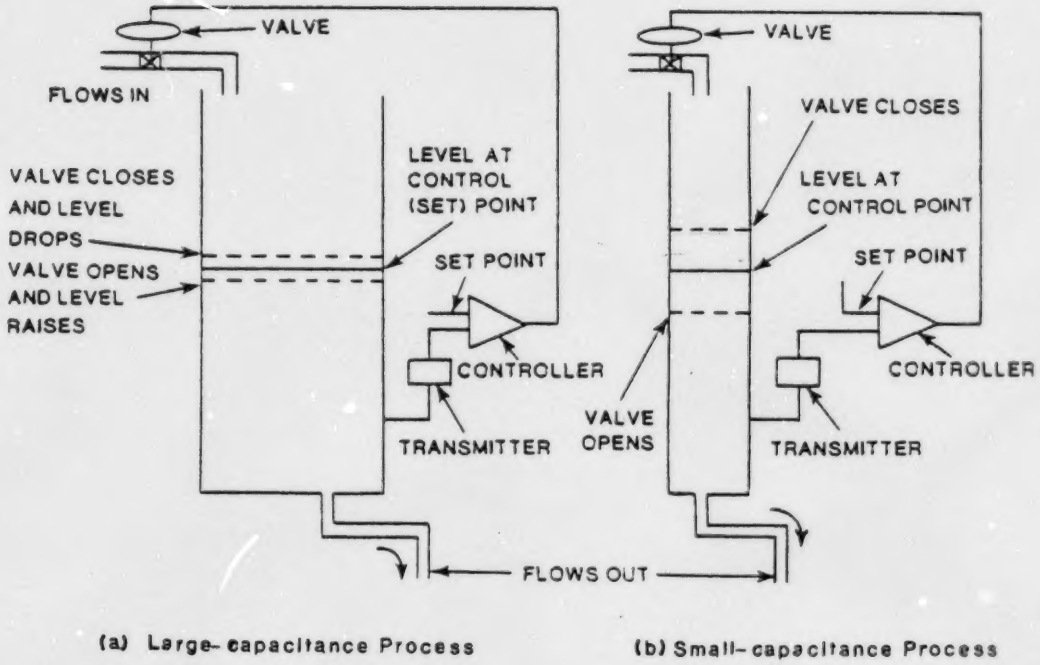



Figure 33-6-11. On-off control.

the procedure will be repeated. The level will never be stable, but will continue to cycle above and below set point as the valve opens and closes.

The cyclic condition of a process controlled by an on-off controller is undesirable in most cases. However, when applied to some processes, the amplitude of the oscillations in the process variable are small and negligible. On-off control is best suited for processes having large capacities and very low dead times. In such processes, (such as those illustrated in Figure 33-6-11a) the energy-storing capability is large; and the rate of change of the process is slow because the material or energy input to the system is small compared to the large capacitance.

As indicated by Figure 33-6-11, the level is in a state of change between points of valve opening and closing. The amplitude of process cycling in Figure 33-6-11a is less than that in Figure 33-6-11b because of the difference in capacitance. The cycles in the large-capacitance process are small and tolerable, but those of the small-capacitance one are unacceptable for most control criteria.

Because of the simplicity of on-off control, it is the system of preference for most large-capacitance systems. On-off control is acceptable where process instability is small and acceptable, as will be true in systems with large capacitance where the process rate of change is slow, with an accompanying short dead time. For other situations (as in Figure 33-6-11b), proportional control should be used.

## PROPORTIONAL CONTROL

For small-capacitance systems, such as the one exhibited in Figure 33-6-11b, proportional control action is necessary to add stability to the process. In this type of control, controller output is proportional to the deviation between process variable and set point. A proportional controller throttles the controller output within a range of control called the "proportional band." This is significant because the controller has the ability to position the control valve such that a balance between supply and demand on a process is maintained.

The throttling range or proportional band is that amount of change in process variable required to cause enough deviation or error signal to produce a one hundred percent change

in controller output. Proportional band and gain are inversely related. Although gain is a unitless ratio of output/input, proportional band is a percent and is expressed as 1/gain x 100%. A controller that has a gain of 2 has a proportional band of 1/2 x 100% = 0.5 x 100% = 50%. This means that a change in process variable of 50% of the maximum measured value will produce a one-hundred-percent change in controller output.

Figure 33-6-12 shows the valve throttling range in relation to gain and proportional band. As the gain is increased, the proportional band is decreased. When the proportional band approaches zero, the gain approaches infinity in accordance with the following relationship:

$$\text{Gain} = \frac{1}{\text{proportional band}} = \frac{1}{0} = \infty$$

Likewise, when the gain approaches zero, the proportional band approaches infinity:

$$\text{Proportional band} = \frac{1}{\text{gain}} \times 100\%$$

$$= \frac{1}{0} \times 100\% \ \infty$$

The gain settings of process controllers, which have adjustable gain settings, are set between 0.2 and 10. The proportional band for these gain settings would be 500% and 10%, respectively. The proper gain setting for a process will depend, among other things, upon the process capacitance and will be the maximum amount for which process stability can be maintained.

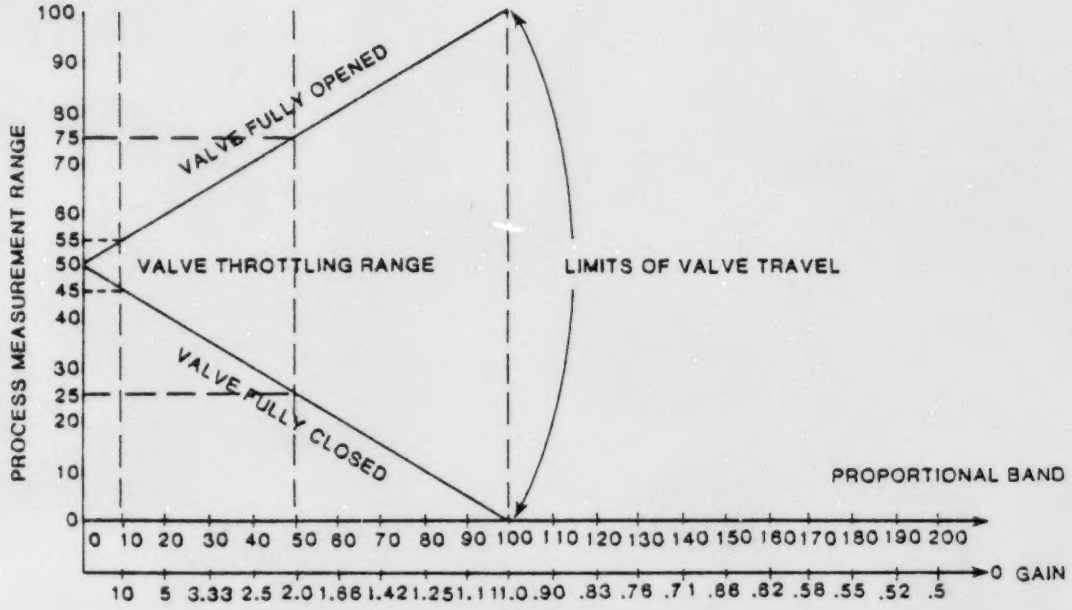



Figure 33-6-12. Relation between throttling range of valve and proportional band or gain.

Figure 33-6-12 demonstrates that the amount of process-measurement change required to produce a full valve throttle varies directly with proportional band and inversely with gain. For a proportional band greater than 100%, the valve will never reach its maximum travel. This would require a process change greater than 100%, which is impossible.

A proportional controller is actuated by the amount of deviation from the set point. When the proportional band is wide, the amount of deviation required to generate an output increases, resulting in residual offset. Residual offset exists when the controller requires a large movement of process variable from the set point for actuation. Offset is an inherent characteristic of processes under proportional control.

Proportional controllers are utilized in processes that have low capacitance and that require better control techniques than are available with on-off control. A bathroom shower is an example of such a process. Control of the water temperature in a shower would produce disastrous results if accomplished by on-off control of water to the shower. The temperature of a large-capacitance process like a bathtub could be maintained by on-off action but the low-capacitance shower would require proportioning of the input water to the process.

The relationship between residual offset and gain can be demonstrated by the process illustrated in Figure 33-6-13. Assume the following initial conditions:

- Level is a set point at 50% of measured value and is constant (PV = SP at 50%).
- Flow in is 12 gal/min.
- Flow out is 12 gal/min.
- Controller gain is 2 (PB = 1/2 x 100 = 50%).
- Controller output is 50% (9 psi).
- Valve signal is 50% (9 psi).
- A 1-psi change in valve signal causes a flow change of 2 gal/min.

For the given conditions, the level will not change, and the controller is maintaining the process at set point by causing the input (flow in) to equal the output (flow out). This condition will be maintained until a process disturbance occurs.

If flow out is increased, the level will decrease until a sufficient amount of deviation in the controller input produces enough controller output to open the valve sufficiently to cause the flow in to equal the flow out. "Residual offset" is the amount of deviation needed to bring about this change.

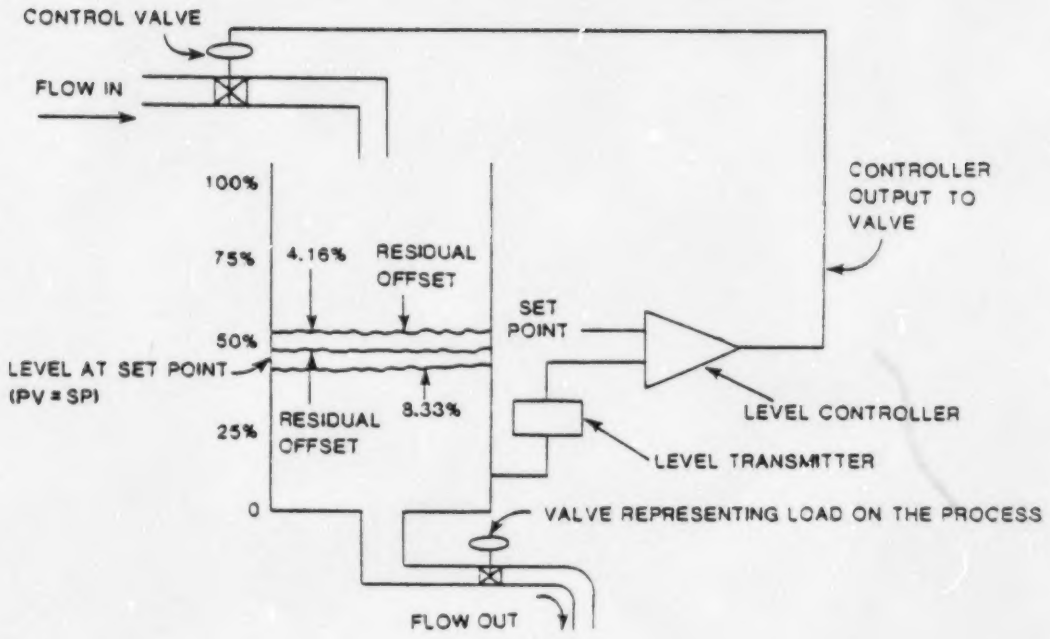



Figure 33-6-13. Residual offset and gain.

For the previously assumed conditions, consider the amount of residual offset that results from a change of water flow rate of 2 gal/min from the tank.

A 2 gal/min increase in flow out will require an increase in flow in of 2 gal/min. The valve signal required for this is 1 psi or 1/12 x 100 = 8.33%, which represents the controller output change required to increase flow into the tank. The level will decrease until the deviation on the controller input increases the controller output by 8.33%.

Relationship between controller input and output is determined by the gain in accordance with Equation 33-6-2 and 33-6-3.

$$\text{output} = \text{gain} \times \text{input} \qquad \text{Eq. 33-6-2}$$

or

$$\text{input} = \frac{\text{output}}{\text{gain}} \qquad \text{Eq. 33-6-3}$$

For an output of 8.33% and a gain of 2, the input is 4.16%. The input of a proportional controller is the deviation between process variable and set point (PV - SP). A level change of 4.16%, therefore, is required to make the flow in equal to the flow out. Once this condition is reached, the process has reached a new stable condition, and the 4.16% offset will remain. The proportional control application just described has achieved a balance between supply and demand in the process, not at the desired condition (SP), but 4.16% away from SP. This may seem insignificant; but as the offset varies inversely with gain, a controller gain of one would double the residual offset.

Values in the previous discussion on residual offset and controller gain are based upon a hypothetical control situation in which the controller is a closed-loop control and assumes a near flow change with valve change.

Although proportional control eliminates the instability of low-capacitance processes, it has the disadvantage of residual offset. To overcome this in low-gain controller applications, another mode of control is required.

## RESET CONTROL

To reduce residual offset, controller gain should be high. For processes in which a high controller gain would result in control instability, the gain must be at a value that would result in excessive residual offset. A control mode known as "reset," or "integral," control returns the process to set point following a load change or other disturbance. The reset function of a controller is used with proportional action and causes controller output to change with time. Output of a proportional-plus-reset controller is a function of the amount of time during which a deviation between process variable and set point exists. Thus, the controller drives the control valve to a position beyond that established solely by proportional action for a period of time, thus returning the process to set point.

The reset output of a proportional-plus-reset controller repeats the initial proportional response and generates a ramp function (Figure 33-6-14); it is measured in minutes per repeat or repeats per minute. The units employed in reset measurement depend upon the controller manufacturer.

In Figure 33-6-14, the step change in the controller input causes an initial proportional output — the amount of which is a function of controller gain. The controller output caused by reset action repeats this proportional output by a linear amount with respect to time. At the end of one reset time unit (usually in minutes), the proportional output has been repeated. The reset output will continue until the process is returned to set point, at which time the output level will be stable and equal to proportional output plus reset output.

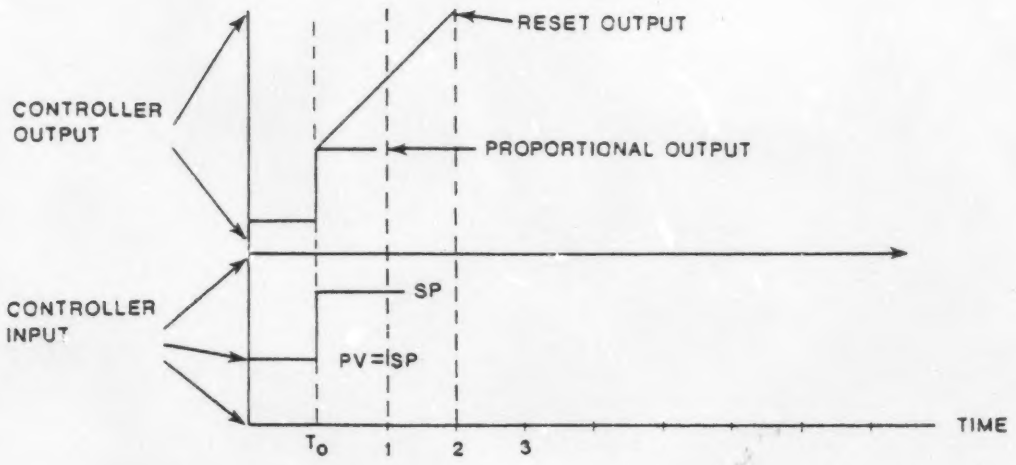



Figure 33-6-14. Output of a proportional plus reset controller (open-loop response).

If process abnormalities prevent the process from returning to set point after reset has driven the controller output to one hundred percent, a condition known as "reset wind-up" exists. This situation is undesirable and is eliminated in some controllers by anti-reset wind-up functions within the controller itself.

Reset control is utilized in processes that require applications of low controller gain. Although some processes in nuclear power plants are applicable to high-gain controllers and could utilize proportional-only controllers, practice generally dictates the use of proportional-plus-reset ones. In initial process design (when control instruments normally are specified and ordered), the actual characteristics of the process probably are not exactly known. The necessity of the control-system hardware usually is established during plant or unit startup, when the process response curve can be produced.

DERIVATIVE CONTROL

Most processes in nuclear power plants are controlled by proportional or proportional-plus-reset control. Situations arise, however, when another form of control is required. A third and final mode of control is incorporated to respond to the rate at which a process is changing and is known as "derivative," or "rate," control. Like reset, derivative control is employed with proportional action.

The unit of derivative is termed "minutes" because it is the time in minutes during which the derivative output leads the proportional output. By leading the proportional output, the derivative control mode produces a lead in the controller output to compensate for dead time and lag time in the process-and-control equipment. The output of a proportional-plus-derivative controller is shown in Figure 33-6-15.

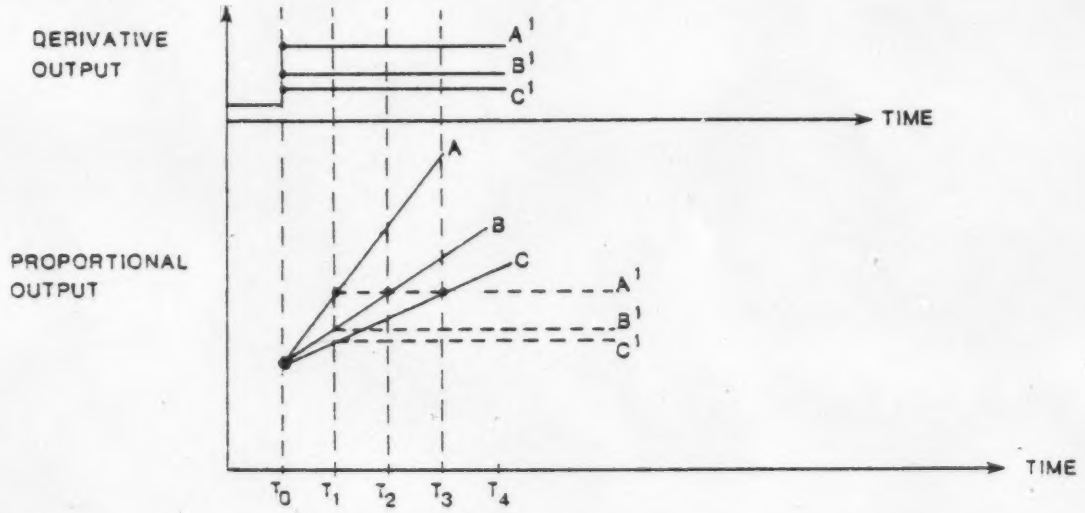



Figure 33-6-15. Proportional-plus-derivative output.

The lower portion of the curve in Figure 33-6-15 represents the proportional outputs of controllers that are changing at different constant rates. The rate of change of outputs is determined by changes in process variable. Remember that the output of a proportional controller is linear with respect to time, and at any instant it is equal to the deviation between process variable and set point multiplied by the controller gain. [output = (PV - SP) (gain)] When the process variable is changing, the proportional output will change at the same rate.

Derivative output, as indicated on the upper portion of the curve in Figure 33-6-15, responds only to a change in deviation. Each change in deviation produces one output, the magnitude of which is a function of the rate at which the process is changing. The derivative output as $T_0$ is $A^1$, which would not occur until $T_1$ with proportional-only control. The same output would not be reached until $T_2$ for a rate of change, as indicated by line B and $T_3$ for C.

Lines A, B, and C in Figure 33-6-15 also could represent the output of controllers with different time settings. The output of $A^1$ is equal to $T_1$ when the derivative time setting is 1; the output at $B^1$ corresponds to a derivative time setting of 0.5; and that at $C^1$ corresponds to a derivative time of 0.33.

Figure 33-6-16 displays the output of a proportional-plus-derivative controller caused by variations in the process producing deviation. Each time the rate of deviation changes, the derivative output changes. When there is no change, there is no derivative output; but the faster the change, the greater the output.

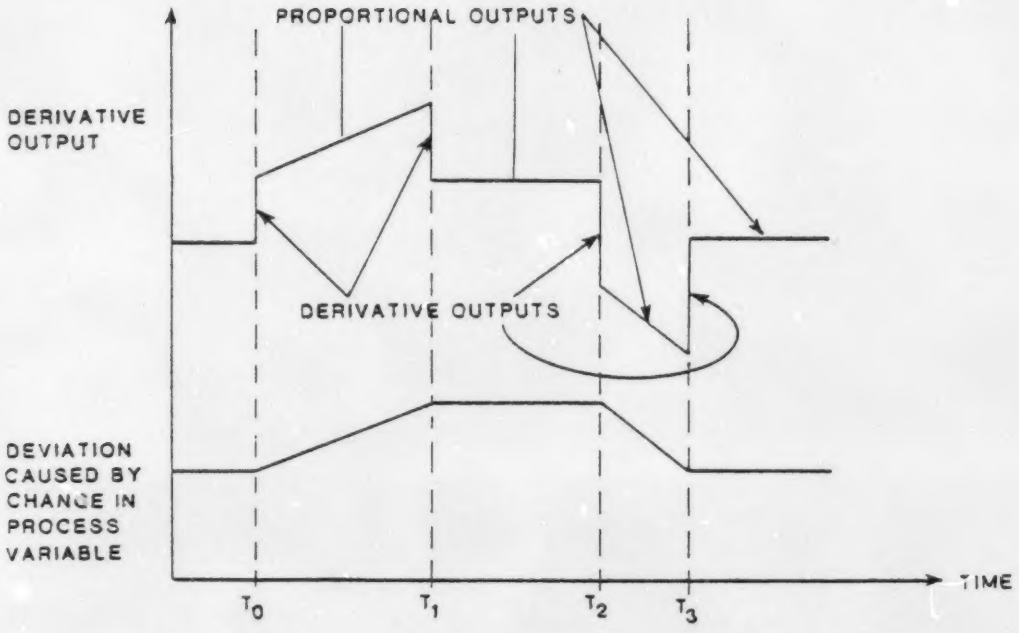



Figure 33-6-16. Proportional plus derivative output.

Derivative control is employed in processes that produce response curves such as those in Figure 33-6-10. When process dead time is long and the rate of process change is fast, the process is most difficult to control, and derivative control is needed. This situation is typical of most temperature processes, which almost always require the use of derivative control.

## EXERCISES

1. Make the following conversions between gain and proportional band (PB):

Gain = 0.5 PB = _____

Gain = 3 PB = _____

Gain = _____ PB = 40%

Gain = _____ PB = 360%

2. For a deviation of 3% between process-variable and set point, determine the output for the following controller settings:

   PB = 20% output = _____

   Gain = 0.4 output = _____

3. If a controller has a gain of 0.2 and a reset time setting of 0.5 minutes/repeat for a process-variable change of 2%, determine the proportional output at time of repeat and the reset output at the end of 1 and 2 minutes. Draw a graph of the outputs.
4. What is the gain of a temperature process if the output of a 4- to 20-mA controller changes 0.5 mA and causes a temperature change of 10°F? The range of the temperature transmitter is 50 to 200°F.
5. For a given process condition, if the controller gain is doubled, how will the residual offset be affected for a proportional-only controller?

## MATERIALS

2 control valves with the following specifications: 3/4" body, pneumatic operated, 3-15 psig. Fisher 512 RGS.

2 d/p cells, pneumatic with input range of 20-205 inches $H_2O$ and output range 3-15 psig. Foxboro 13A.

2 controllers with fast chart drive; pneumatic with proportional, reset, and derivative; input and output range of 3-15 psig. Foxboro Model 120.

1 orifice meter with 1/2 concentric orifice. Perry Equipment Corp. Type 120.

1 pump – 3/4" with 1/2 H.P. motor. Jacuzy 3RM2S$^{1}$/A.

1 tank to be used for a level process.

8 ft of 12" PVC pipe capped at each end, with appropriate fittings for pump and instrument connections.

1 tank to be used as a reservoir – approximately 50 gallon capacity.

Manufacturer's instruction booklet for instruments and equipment.

Assorted piping, tubing, and wiring to connect the equipment.

## PROCEDURES

### PROCEDURE I

1. Follow manufacturer's recommended installation and startup procedures, and connect the equipment to construct a flow-and-level loop as shown in Figure 33-6-17.
2. With both controllers on manual control, stroke each valve from the controller to determine valve operation as signal-to-open or signal-to-close.
3. Close both valves.
4. Fill reservoir with water; start pump.

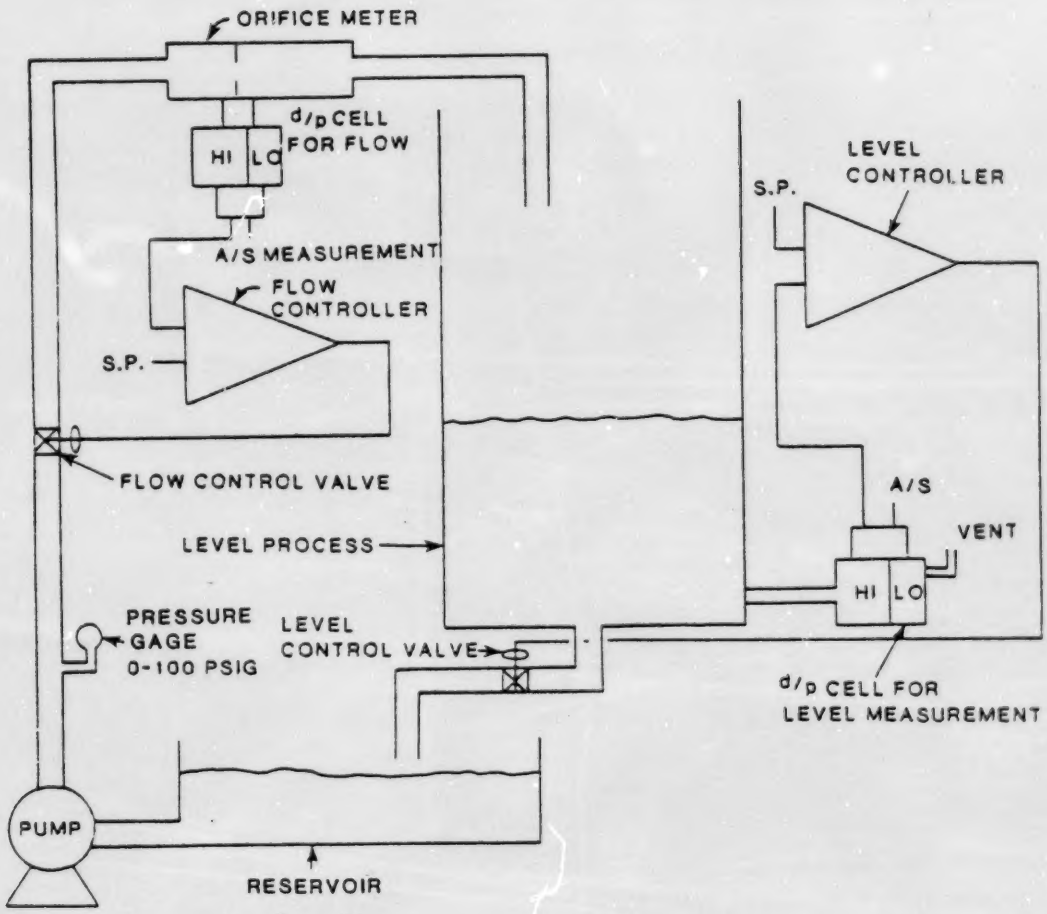



Figure 33-6-17. Flow-level process for procedure I.

5. Open flow control valve (FV) slowly until an indication of flow is indicated by flow controller. With flow valve, establish flow at about 50% of full-scale value.
6. When level in the tank reaches 50% of full-scale value as indicated by the level controller, open level control valve (LV) to maintain level at this value.
7. Continue to mainpulate FV and LV until flow is 50% and level is constant at 50%.

8. From valve operations as determined in Step 2, select proper controller action for each loop to provide negative feedback. Locate controller action switch; place it in proper position.
9. Adjust reset and derivative settings for minimum amount. Position proportional band setting on 400%.
10. Using smooth, bumpless transfer procedures as outlined in instruction manual, switch level controller to automatic.
11. Note level value at this time; it still should be about 50%, and reduce the flow in by 10%.
12. Note a change in level and, when it is again stable, note the new value. Difference in the level values is caused by residual offset. Enter controller gain and offset in Data Table 33-6-1.
13. Adjust the FV for the original flow value, increase by 10%.
14. Using smooth bumpless transfer procedures, switch controller to manual and double the controller gain.
15. Repeat Steps 10 through 14.
16. Repeat Step 15 until Data Table 33-6-1 is complete.
17. Repeat Step 14. Procedure is now complete. Close both valves (LV and FV); stop pump.

PROCEDURE II

1. Perform the first nine Steps of procedure I.
2. Locate chart drive speed switch; place it in the fast position. Note: Omit this Step for instruments that have only a single chart speed.

3. Make a step change in input of the flow controller; observe the process response on the chart. Note gain and phase shift relationship.
4. Make a step change in input of level controller; observe the process response on the chart. Note the gain phase-shift relationship.
5. From observations in Steps 3 and 4, determine probable control modes required to control the process.
6. Close both valves; stop pump. Procedure is now complete.

DATA TABLE 33-6-1

| | Controller Gain | Offset |
|---|---|---|
| Trial 1 | | |
| Trial 2 | | |
| Trial 3 | | |
| Trial 4 | | |
| Trial 5 | | |

# REFERENCE MATERIALS

Anderson, Norman A. Instrumentation for Process Measurement and Control. 2nd ed. Norwood, MA: Chilton Company, 1972.

Johnson, Curtis D. Process Control Instrumentation Technology. 1st ed. New York: John Wiley and Sons, 1977.

Shinsky, F. G. Process Control Systems. 1st ed. New York: McGraw-Hill Book Company, 1967.

1. Define and explain the following terms:
   a. On-off control.

   b. Proportional control.

   c. Reset control.

   d. Derivative control.

   e. Process stability.

f. Residual offset.

g. Process gain.

h. Phase shift in a process.

2. List process characteristics that determine the need for each control mode.

3. List the probable control mode needed to control the process studied in the Procedures section of this module.

4. What is the relationship between controller gain and process stability?

5. What is the relationship between controller gain and residual offset.

# NUCLEAR TECHNOLOGY

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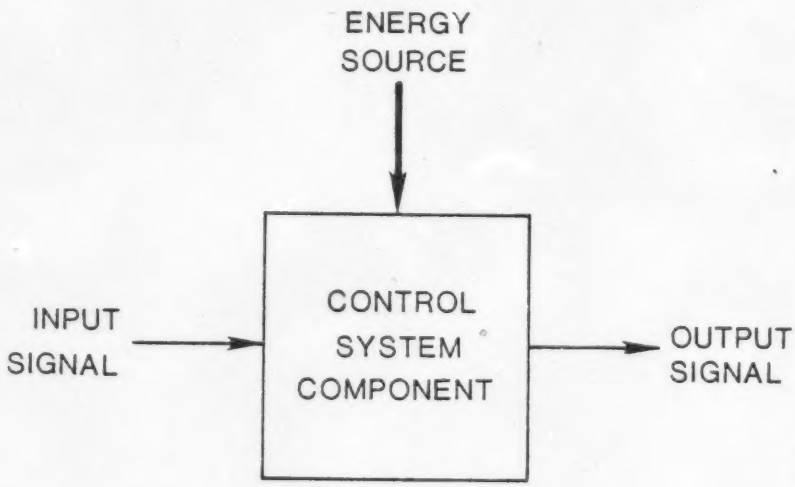


CONTROL SYSTEMS I
COURSE 33

ORD CENTER FOR OCCUPATIONAL RESEARCH AND DEVELOPMENT

NUCLEAR TECHNOLOGY SERIES

INDEX

for

COURSE 33, CONTROL SYSTEMS I (SIX MODULES)

NOTE: Each module in this Course is numbered separately, and the page numbers begin with page 1 in each module. Therefore, this Index lists for each entry the module number (underlined), followed by a comma and the page number. Figures and tables are listed by their numbers, followed by the module and page number in parentheses. A Master Index is available in a separate volume. This general index merges all index entries from the 35 Nuclear Courses. It is a valuable research tool, with which the student or researcher can locate all the references to any subject within the 35 Courses.


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